Terahertz Technology and Applications

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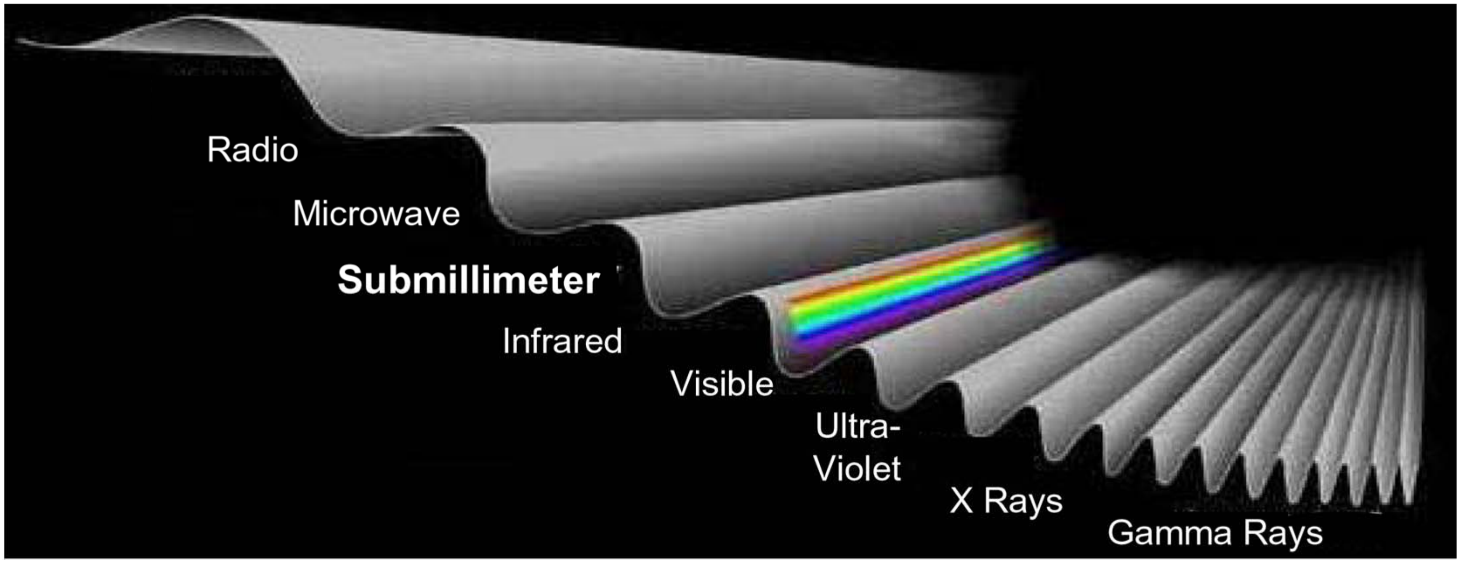
Terahertz (Submillimeter) Waves


Radio
Microwave
Submillimeter
Infrared
Visible
Ultra-Violet
X Rays
Gamma Rays

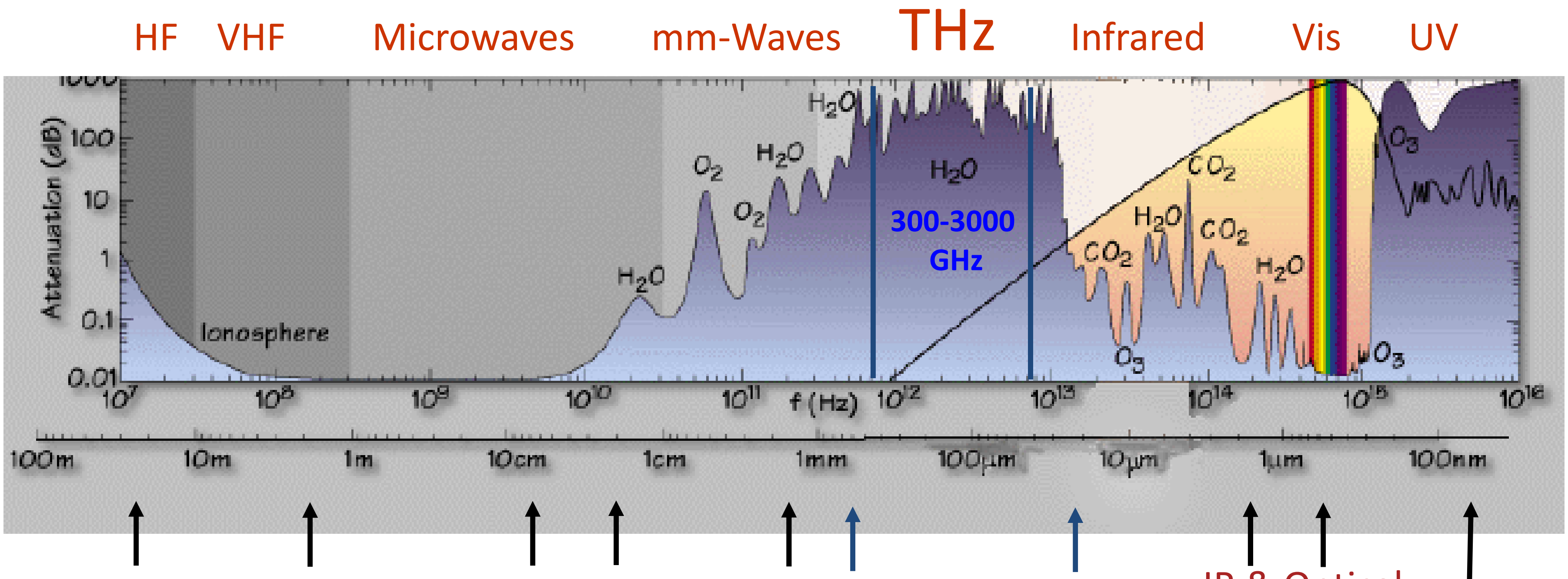
Loosely defined: 1 mm > λ > 100 μm

300 GHz < ν < 3 THz

Most of the radiation in the Universe is emitted at submillimeter-wavelengths, peaking at 3 THz (if we exclude Cosmic Microwave Background).

Atmospheric Transmission

NASA is interested in the THz band. Strong water and oxygen absorption in the atmosphere make high altitude platforms essential for good seeing.



HF VHF Microwaves mm-Waves THz Infrared Vis UV

300-3000 GHz

Ionosphere Opaque

Radio Window

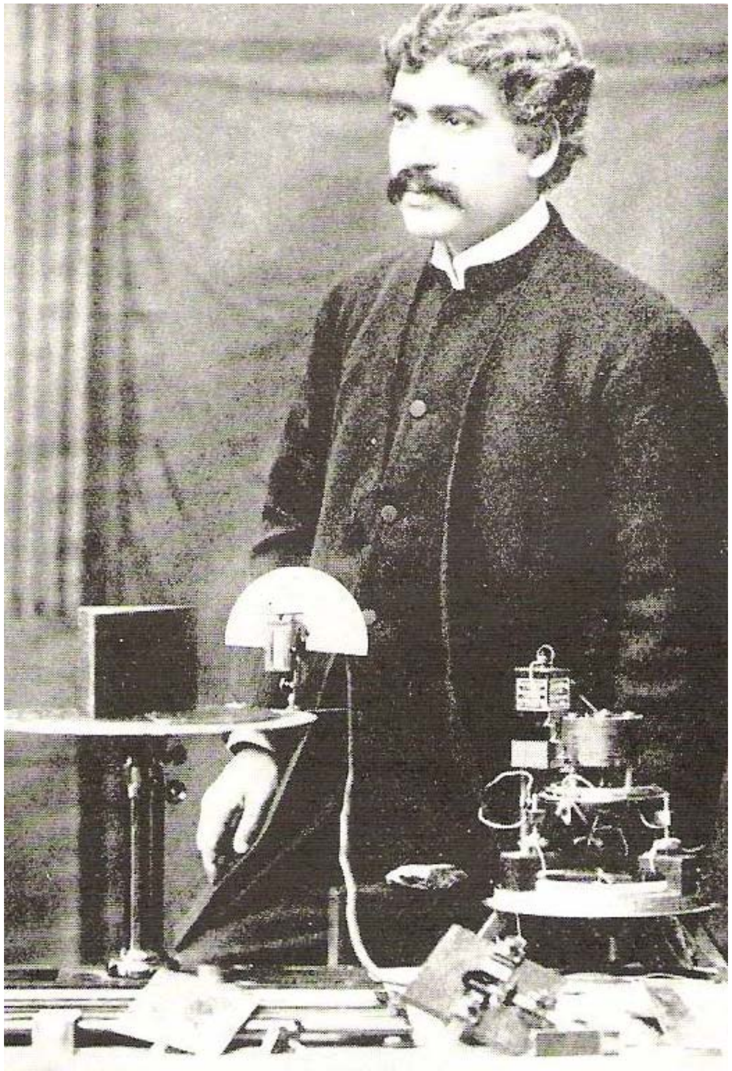
Mountain top Transmission Acceptable

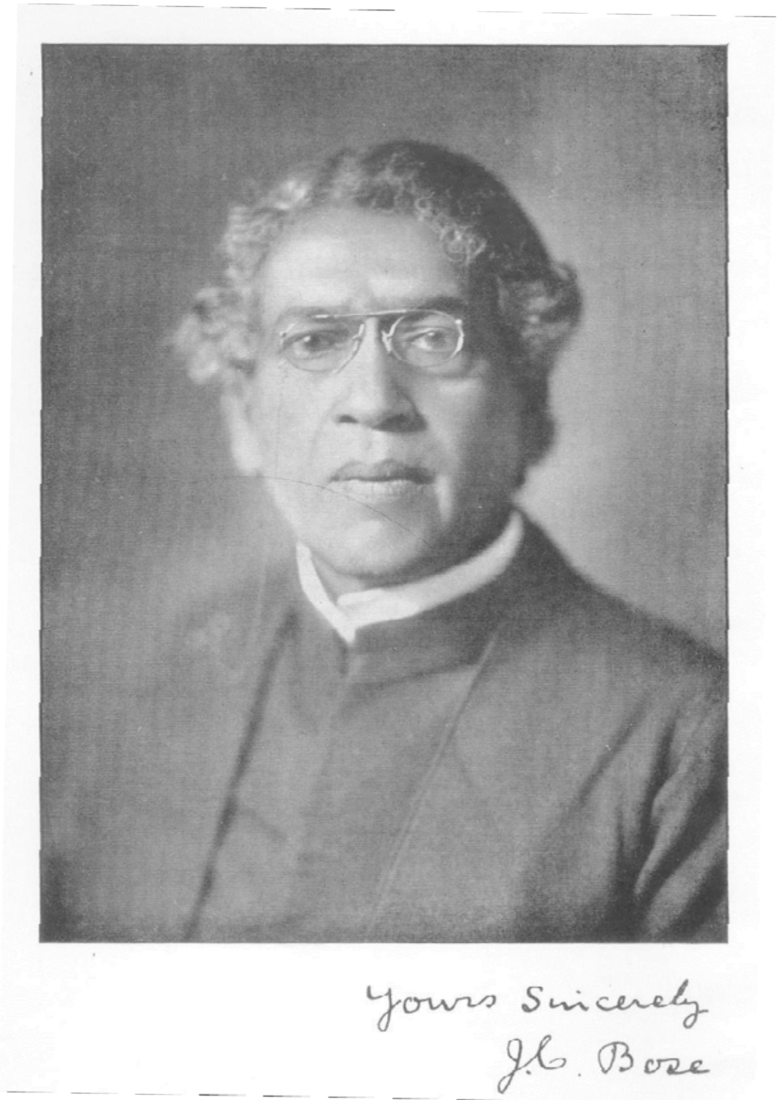
Atmosphere Opaque

IR & Optical Windows

Atmosphere Opaque

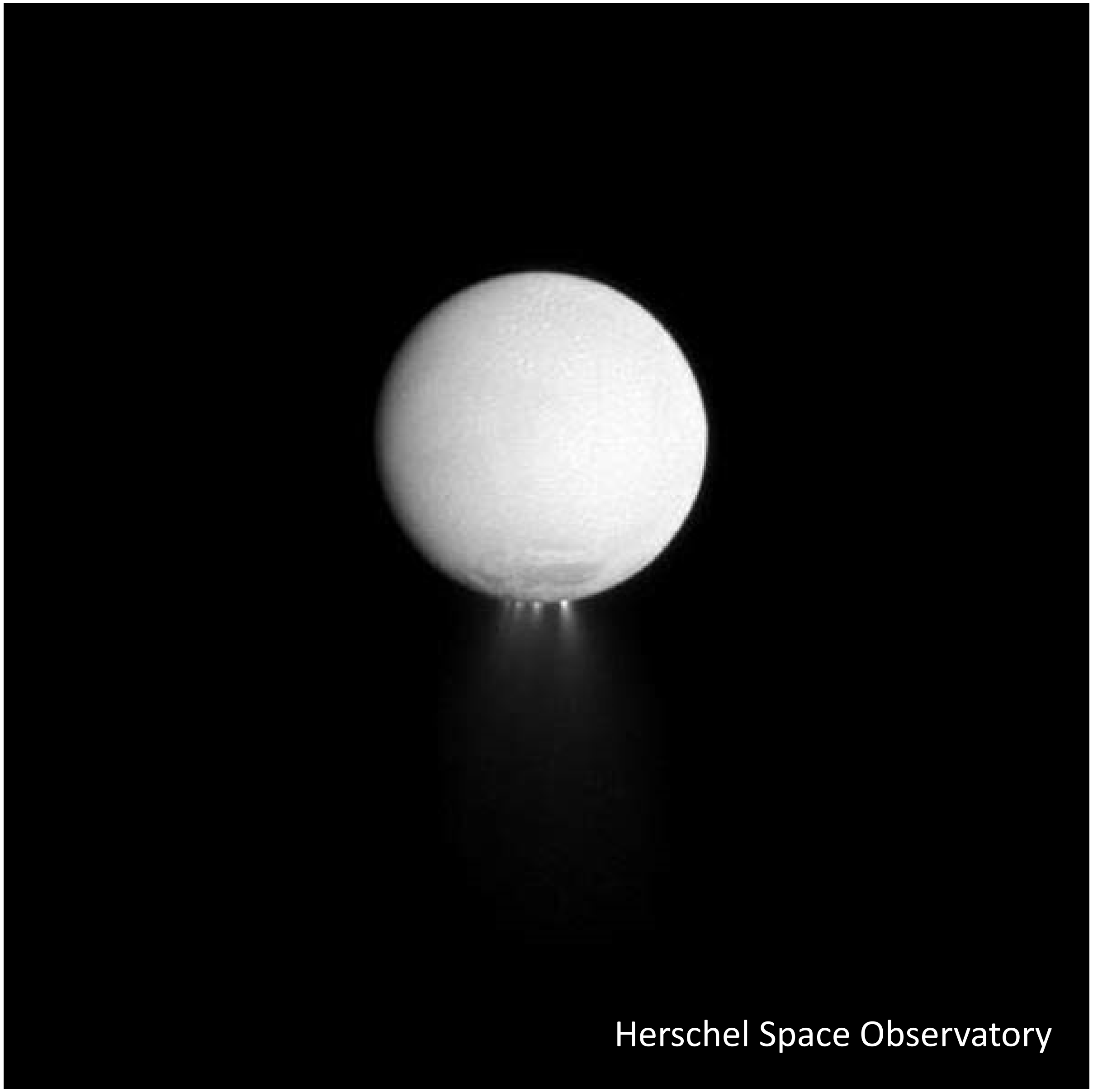
Prof. J. C. Bose and Terahertz




Yours Sincerely
J.C. Bose

Prof. J. C. Bose laid the foundation of Terahertz Technology with his work at millimeter-waves in 1890s.

Terahertz Science: Planetary Bodies


Herschel Space Observatory

Saturn’s moon Enceladus rains down water on Saturn!

Now we know where the water vapor in Saturn’s upper atmosphere come from!

Enceladus is the only moon in the Solar System known to influence the chemical composition of its parent planet.

Terahertz Science: Oxygen Molecule

2 August 2011 Last updated at 10:53 ET

1,171 Share

Oxygen finally spotted in space

"Hidden" oxygen may be released from dust grains and ice in star-forming regions

One of astronomy's longest-running "missing persons" investigations has concluded: astronomers have found molecular oxygen in space.

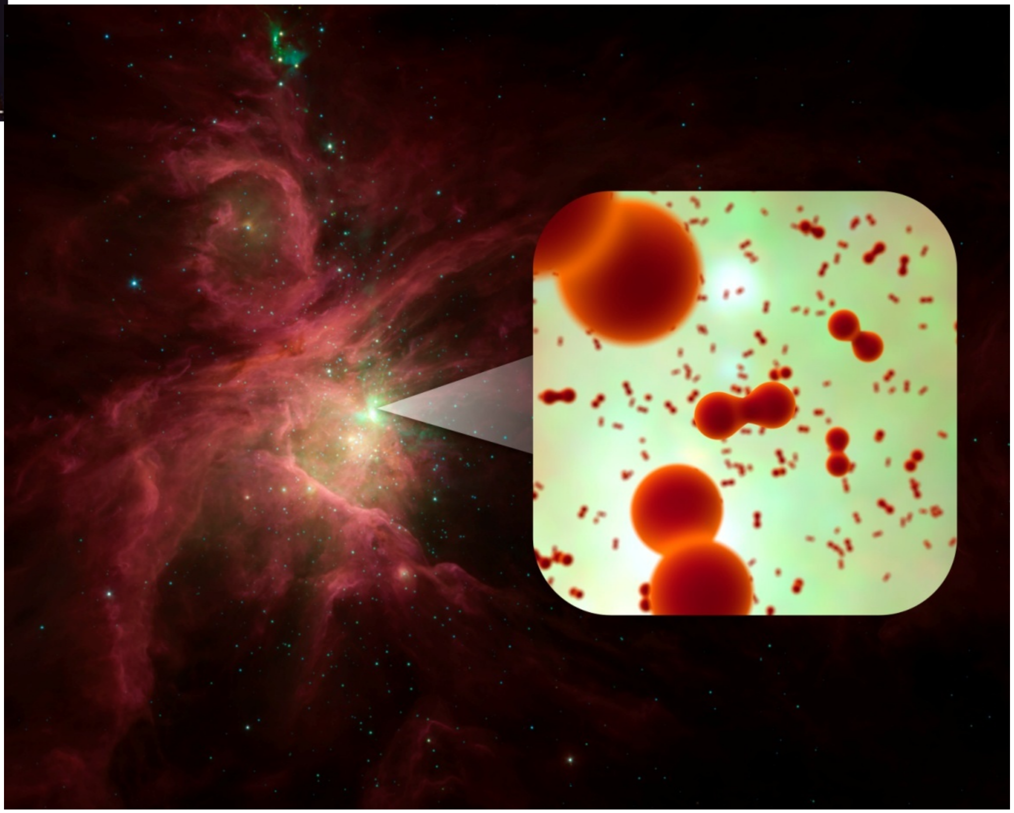
While single atoms of oxygen have been found alone or incorporated into other molecules, the oxygen molecule - the one we breathe - had never been seen.

The Herschel space telescope spotted the molecules in a star-forming region in the constellation of Orion.

The find **will be published in the Astrophysical Journal**.

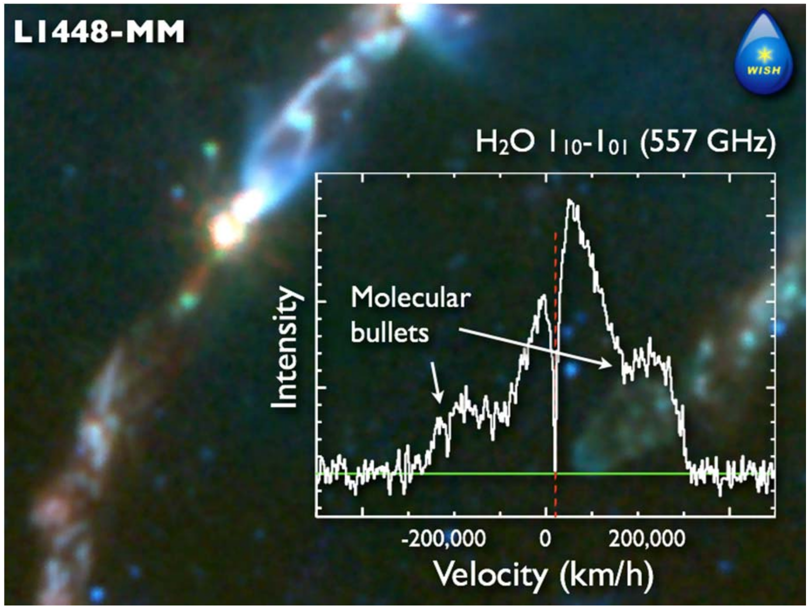
From BBC News: "http://www.bbc.co.uk/news/science-environment-14372708"

Herschel Space Observatory's HIFI Instrument



Ref: Paul Goldsmith et. al.,

Terahertz Science: Water

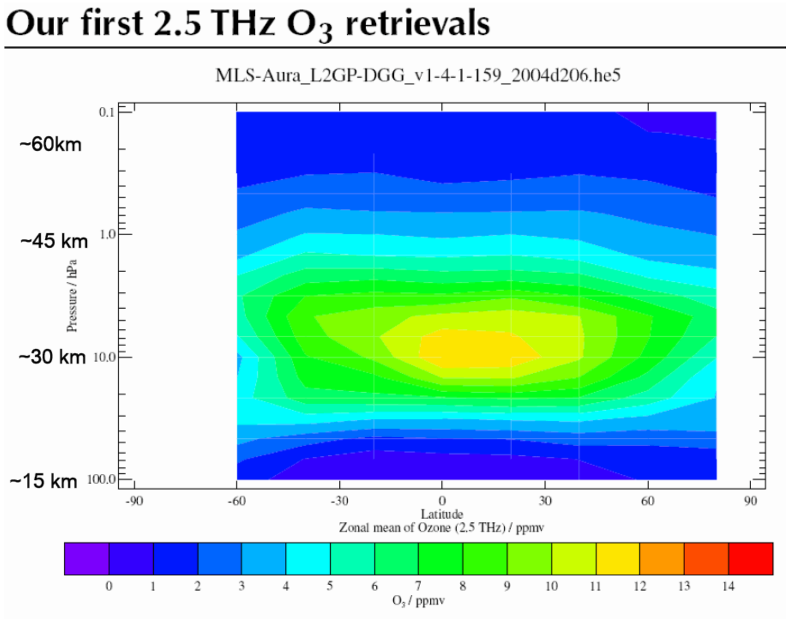


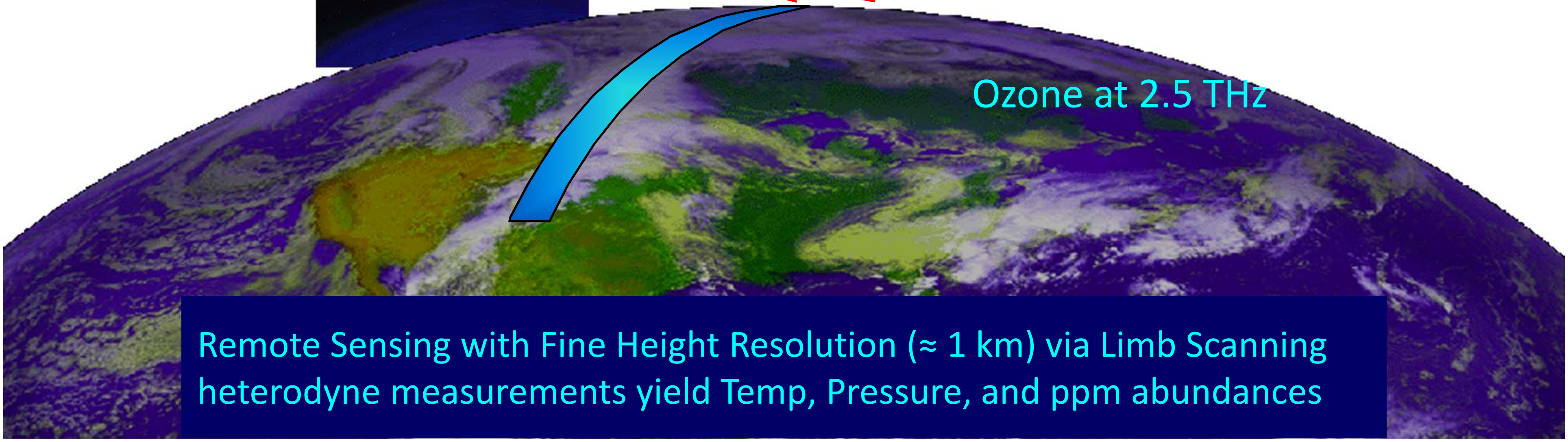
Observations with Herschel-HIFI of water in a young Sun-like star reveal high-velocity "bullets" moving at more than 200,000 km/h from the star. This can be compared to the velocity of a bullet from an AK47 rifle, which is 2500 km/h or 80 times slower. It is a surprise that water molecules are observed at this high velocity - they should have been destroyed in the shock where temperatures exceed **100,000 degrees**.

Observations reveal that water very likely reforms rapidly in the hot and dense shocked gas. **The conditions are so favorable that approximately 100 million times the amount of water in the Amazon river is formed, every second!**

Earth Science Applications

- Stratospheric and Tropospheric Chemistry
  - ozone layer modeling
  - economics vs. environment
  - water distribution/pollutants
- Clouds: Global Warming
  - ice crystal: size & distribution
- Aerosols, Volcanism, Dust

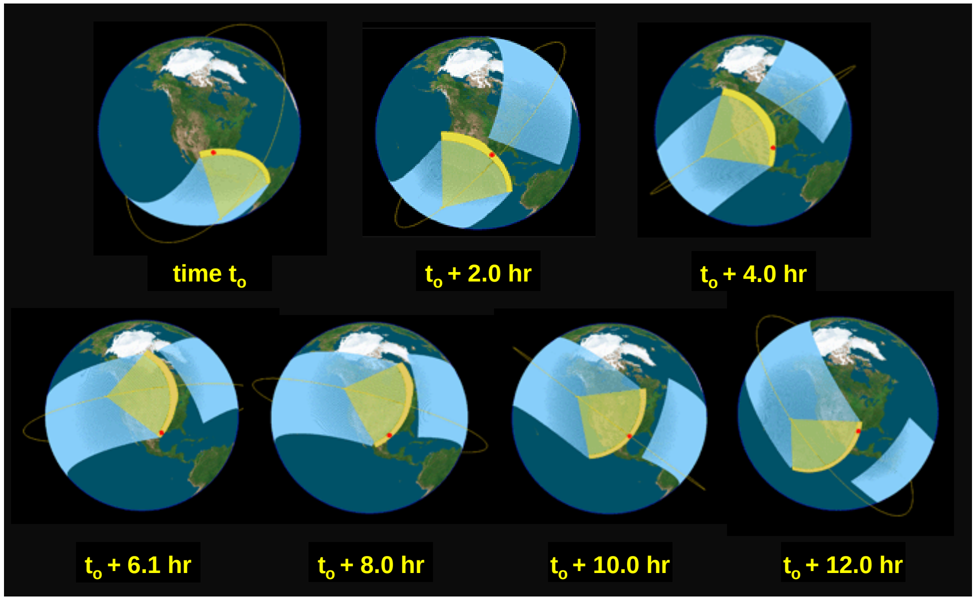




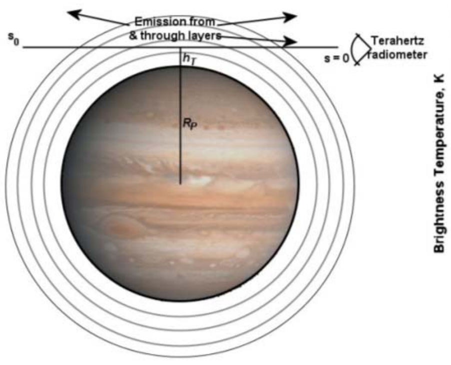
Remote Sensing with Fine Height Resolution (≈ 1 km) via Limb Scanning
heterodyne measurements yield Temp, Pressure, and ppm abundances

Earth Science Applications

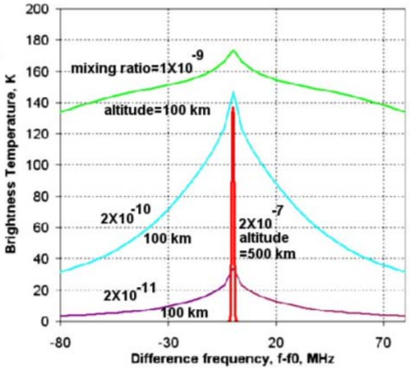
Microwave Limb Sounder (MLS):


time t_o
t_o + 2.0 hr
t_o + 4.0 hr
t_o + 6.1 hr
t_o + 8.0 hr
t_o + 10.0 hr
t_o + 12.0 hr

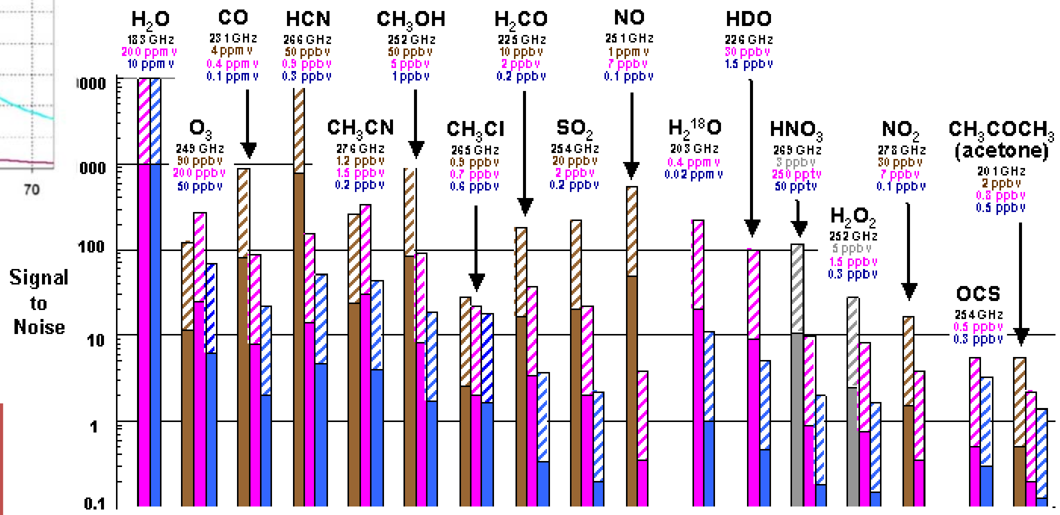
150-300 GHz,
600 GHz, 2500 GHz sensors


Emission from
& through layers
s_0
s = 0
Terahertz
radiometer
h_T
R_P

(a)



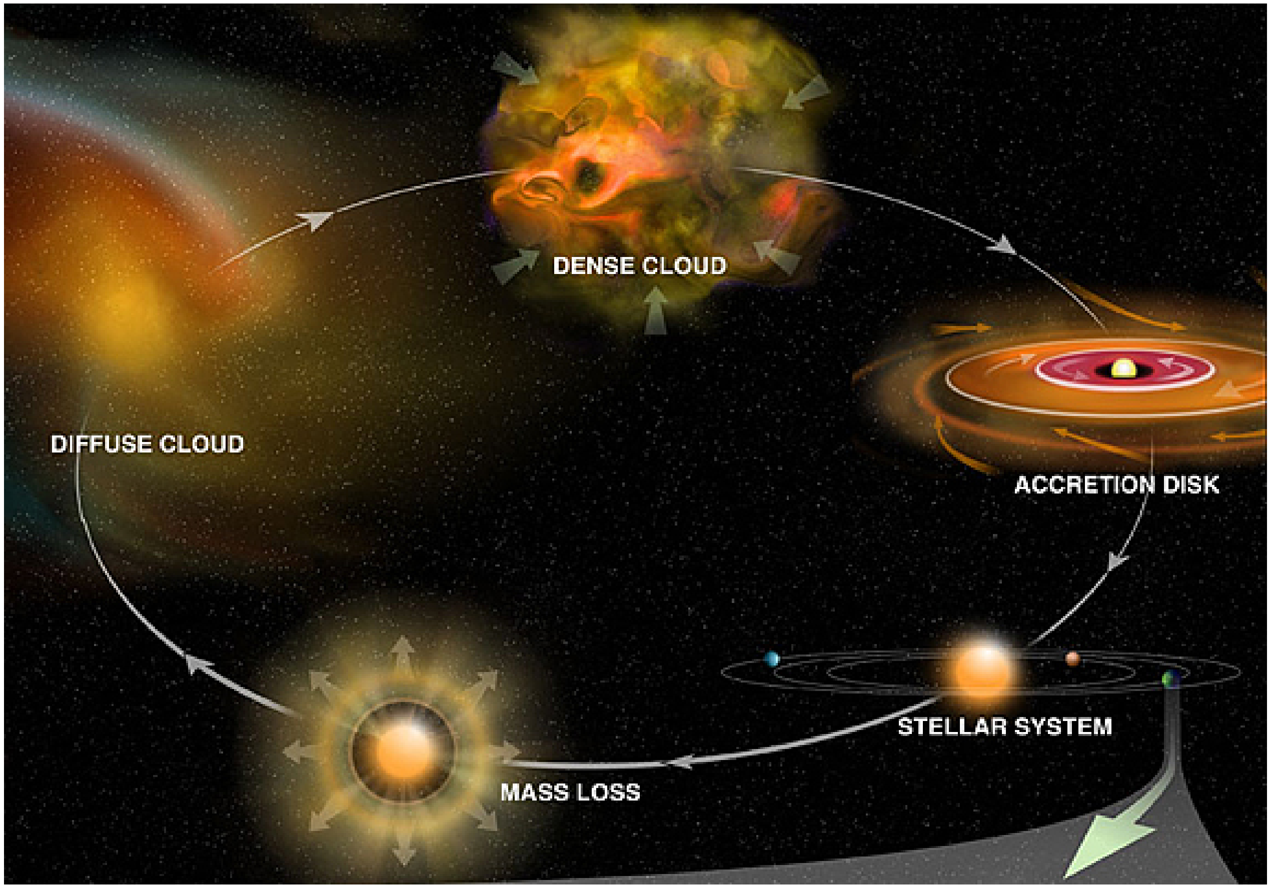
(b)



Atmospheric Chemistry, Air Pollution, and Global Monitoring

Astrophysics Applications

THE STAR FORMING CYCLE


DENSE CLOUD
ACCRETION DISK
STELLAR SYSTEM
MASS LOSS
DIFFUSE CLOUD

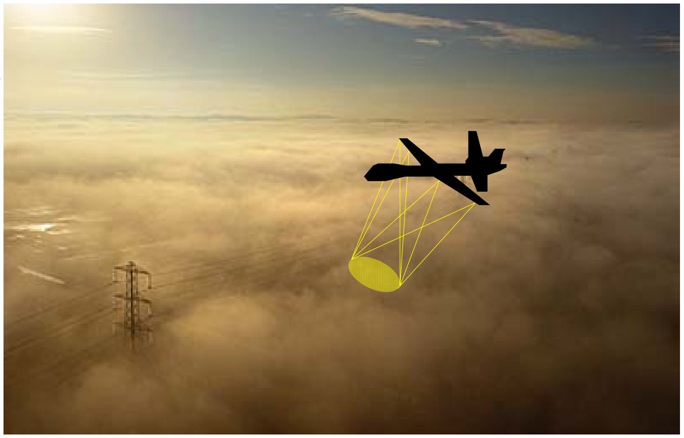
Star formation and galaxy evolution occur in region enshrouded by dust that obscures them at infrared and optical wavelengths.

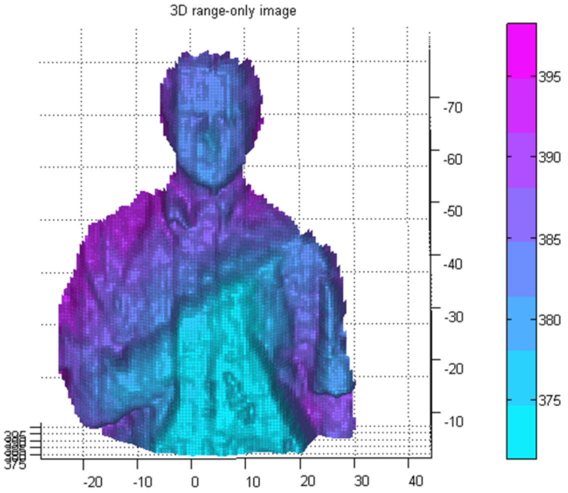
In the interstellar medium, the high temperature excites a wealth of spectral lines at terahertz frequencies.

Security Applications

Stand-off explosive detection, and reconnaissance.

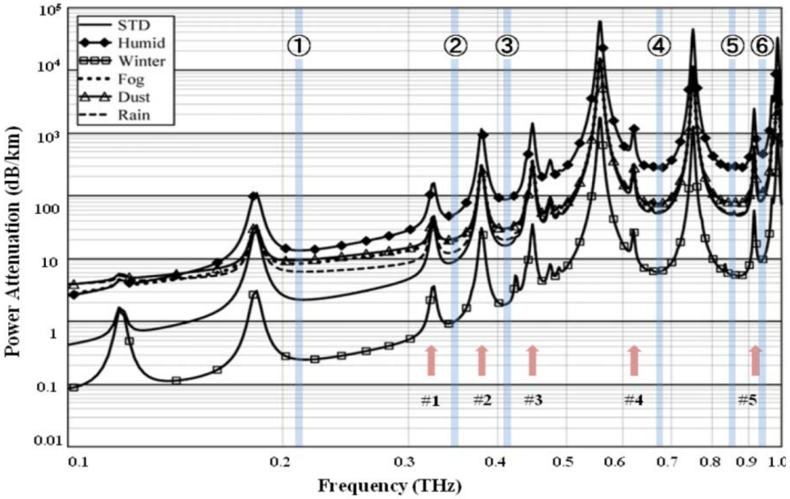
- High Resolution, Penetrates Dust, Smoke, Fog, Clothes.

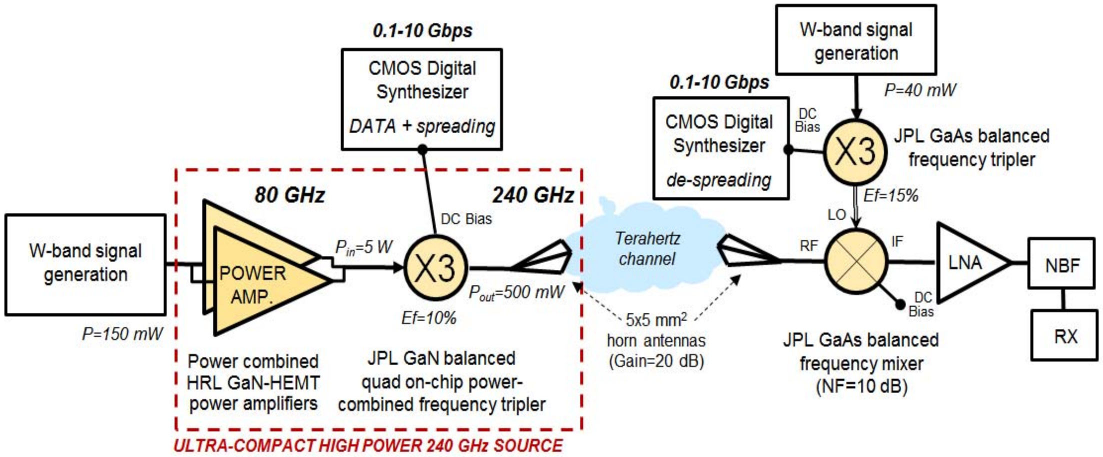




Advantages of Terahertz Communications

- Highly directional beams compared to current microwave communications
- Less scattering of radiation compared to infrared (IR) wireless and better penetration through rain and clouds
- Limited propagation distance due to atmospheric attenuation in order to avoid signal interception out of the line of sight
- Much larger channel bandwidth for spread spectrum techniques which enable a strong anti-jamming and very low probability of detection systems
- Hidden signals in the background noise



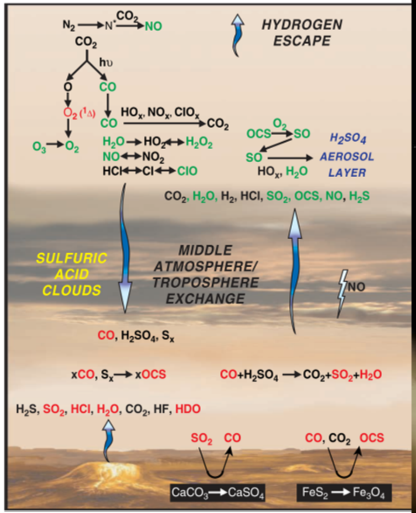


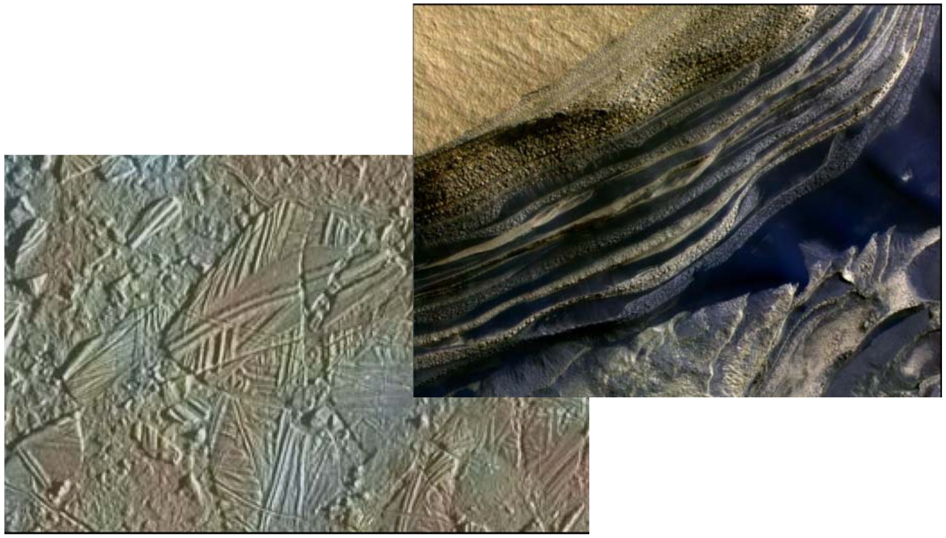
0.1-10 Gbps
CMOS Digital Synthesizer
DATA + spreading
W-band signal generation
P=150 mW
80 GHz
POWER AMP.
240 GHz
DC Bias
P_{in}=5 W
X3
P_{out}=500 mW
Ef=10%
Power combined HRL GaN-HEMT power amplifiers
JPL GaN balanced quad on-chip power-combined frequency tripler
ULTRA-COMPACT HIGH POWER 240 GHz SOURCE
Terahertz channel
5x5 mm² horn antennas (Gain=20 dB)
0.1-10 Gbps
CMOS Digital Synthesizer
de-spreading
W-band signal generation
P=40 mW
DC Bias
X3
JPL GaAs balanced frequency tripler
Ef=15%
LO
RF
IF
DC Bias
JPL GaAs balanced frequency mixer (NF=10 dB)
LNA
NBF
RX

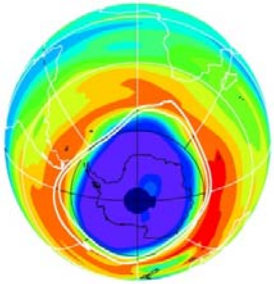
Technology Driven by Science: Finding Other Applications

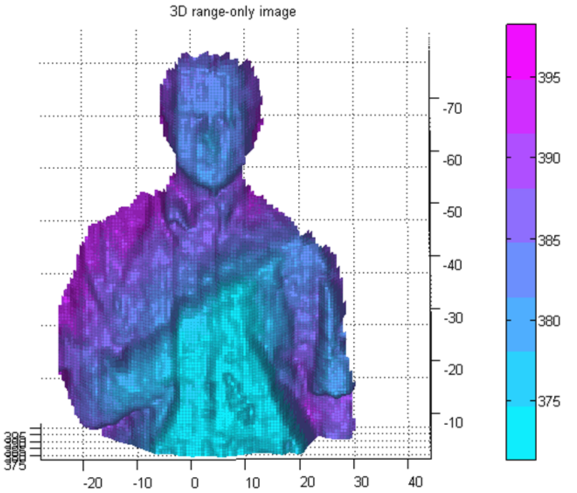
Radiation in these wavelengths highlights:

- Star and Galaxy Formation
- Dust and Gas Chemistry
- Cosmology and CMB Astrophysics
- Atmospheric Constituents and Planet Dynamics
- Global Atmospheric Monitoring
- Security Applications
- Wireless Power Transfer


$N_2 \rightarrow N^* \xrightarrow{CO_2} NO$
CO_2
$h\upsilon$
O
CO
$O_2(^1\Delta)$
CO $\xrightarrow{HO_x, NO_x, ClO_x}$ CO_2
$O_3 \rightarrow O_2$
$H_2O \rightarrow HO_2 \leftrightarrow H_2O_2$
$NO \leftrightarrow NO_2$
$HCl \leftrightarrow Cl \leftrightarrow ClO$
HYDROGEN ESCAPE
$OCS \xrightarrow{O_2} SO$
SO
HO_x, H_2O
H_2SO_4 AEROSOL LAYER
$CO_2, H_2O, H_2, HCl, SO_2, OCS, NO, H_2S$
SULFURIC ACID CLOUDS
MIDDLE ATMOSPHERE/ TROPOSPHERE EXCHANGE
NO
CO, H_2SO_4, S_x
$xCO, S_x \rightarrow xOCS$
$CO + H_2SO_4 \rightarrow CO_2 + SO_2 + H_2O$
$H_2S, SO_2, HCl, H_2O, CO_2, HF, HDO$
SO_2 CO
CO, CO_2 OCS
$CaCO_3 \rightarrow CaSO_4$
$FeS_2 \rightarrow Fe_3O_4$







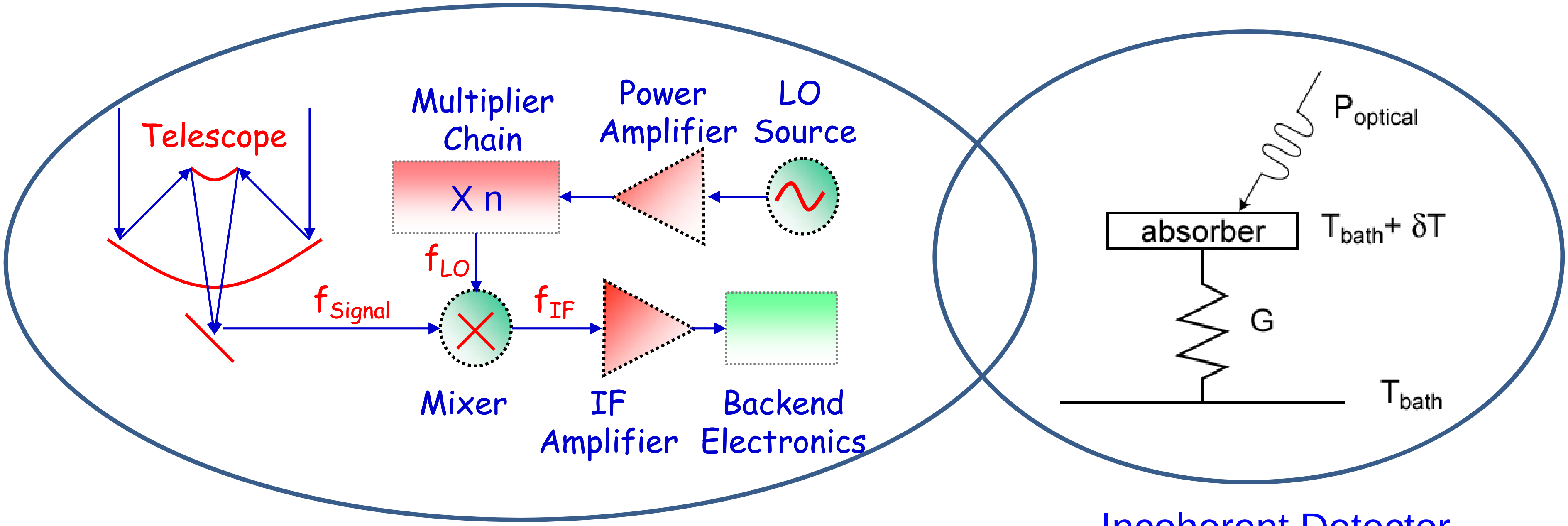
Terahertz Sensors: Direct and Coherent Detectors

The sensors at submillimeter wavelengths can be broadly categorized into two distinct sets: *Coherent detectors* and *Incoherent (direct) detectors.*

At terahertz frequencies:

Coherent detection is mostly done using heterodyne techniques.

Incoherent detection: the submillimeter-wave photons are directly absorbed by some material, creating either electronic excitations or thermal energy (heat). In the later case, the sensor is called a bolometer.


Telescope
Multiplier Chain
X n
Power Amplifier
LO Source
f_{LO}
f_{Signal}
f_{IF}
Mixer
IF Amplifier
Backend Electronics
$P_{optical}$
absorber
$T_{bath} + \delta T$
G
T_{bath}

Coherent Detector

Incoherent Detector

Direct and Coherent Detectors

The primary distinction between coherent and incoherent (or direct) detection is the presence or absence of quantum noise.

Coherent receivers preserve information about both the amplitude and phase of the electromagnetic field while providing large photon number gain.

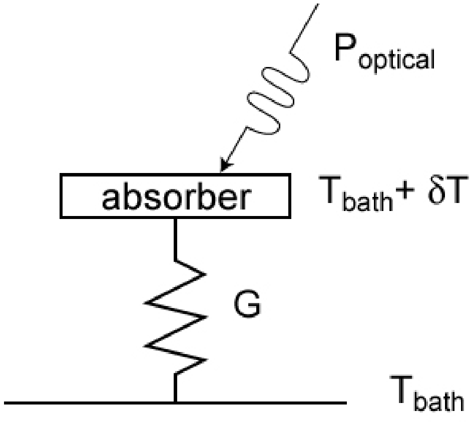
As a result, coherent receivers are subject to quantum noise, which can be expressed as a minimum noise temperature of Tn = hν/kB, or 48 K/THz.

Quantum noise is equivalent to the shot noise produced by a background radiation flux of one photon per second per Hertz of detection bandwidth.

At radio wavelengths, the background is significantly larger than this value and in any case never falls below the 2.7 K cosmic microwave background (CMB), and so the use of coherent receivers at radio wavelengths need not lead to a loss of sensitivity.

In contrast, at optical or infrared wavelengths the quantum noise of coherent receivers is intolerably large, far larger than the typical backgrounds, and so direct detection is strongly preferred.

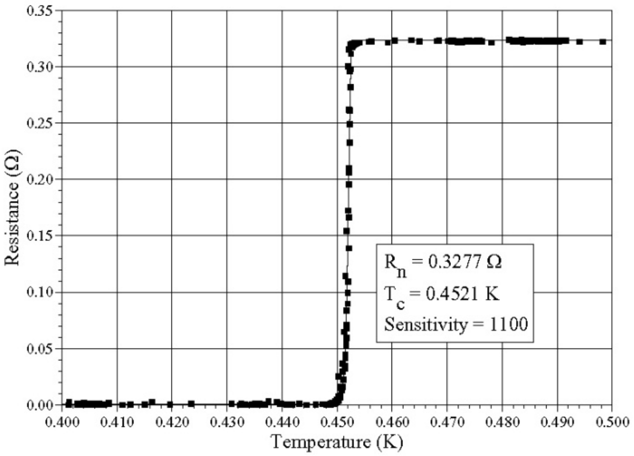
Terahertz Direct Detectors

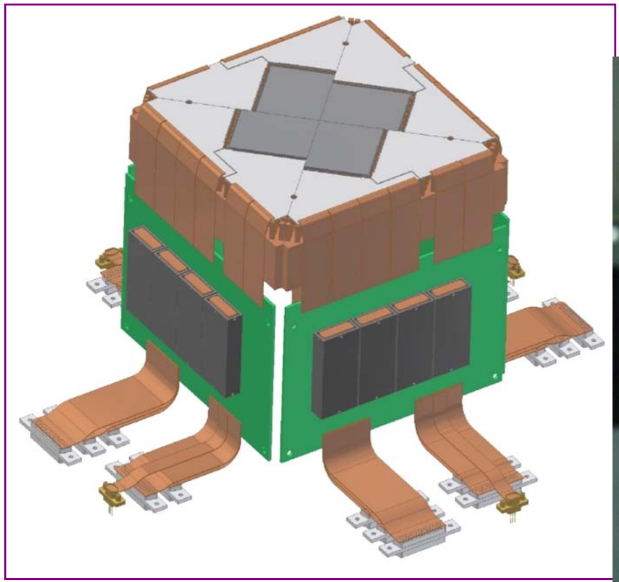

$P_{optical}$
absorber
$T_{bath} + \delta T$
G
T_{bath}

Bolometers:

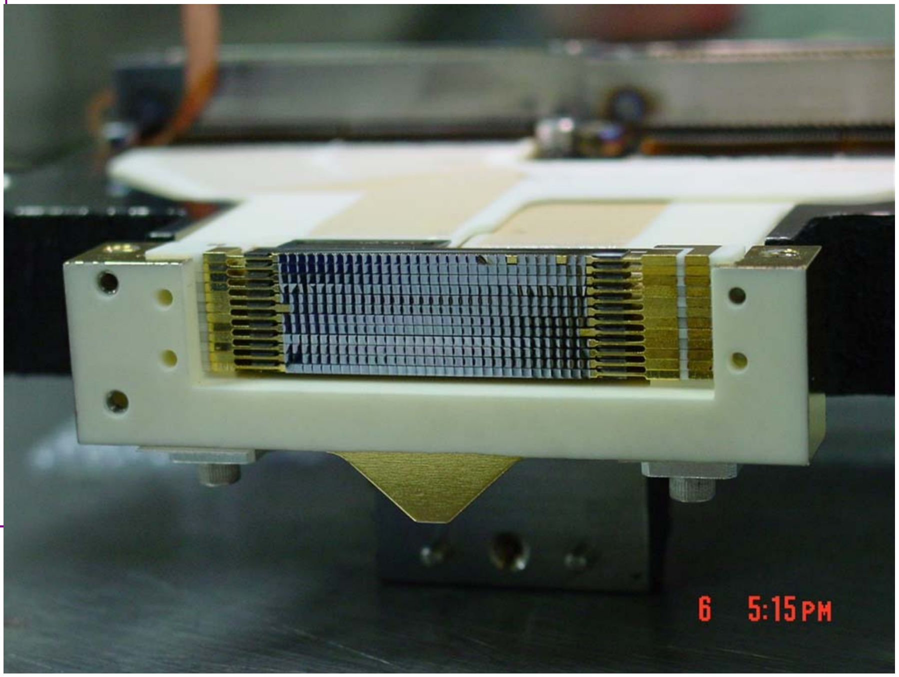
Good continuum sensitivity

- Wide optical bandwidth
- Low NEP
- Can reach photon noise limit
- Good Thermistors (TES)
- Needs cryogenic cooling





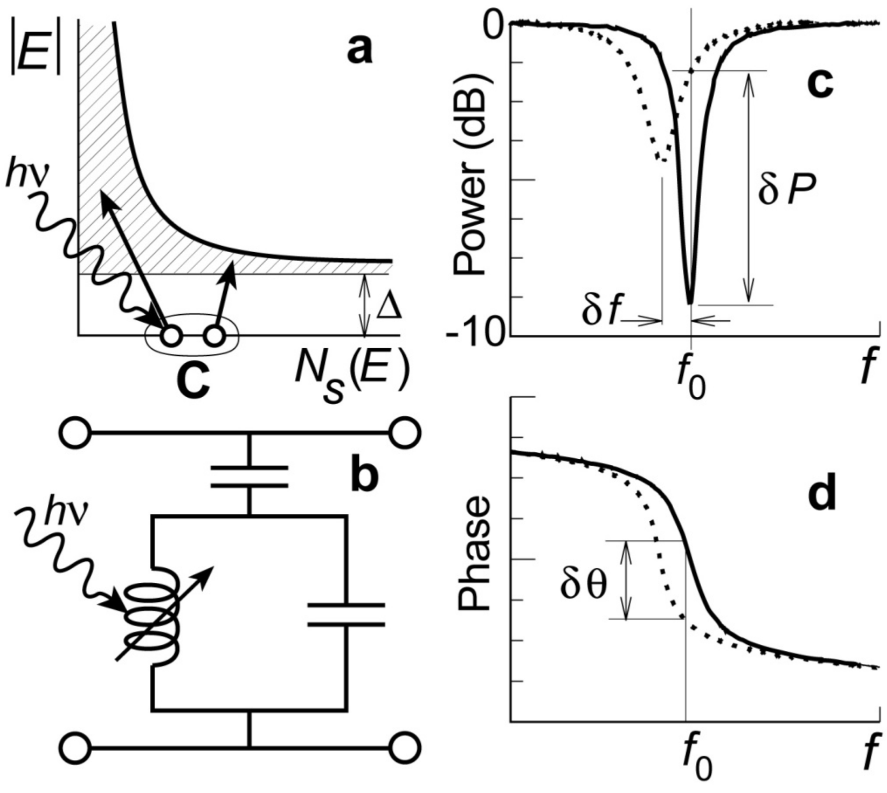
SCUBA II Multiplexed
TES Bolometer Array



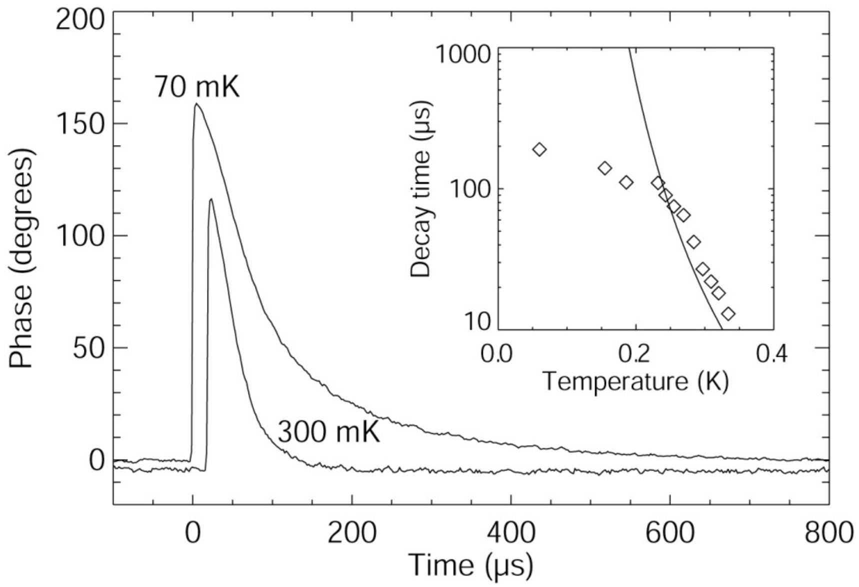
SHARC II
384 Pop-Up
Pixels with
Implanted
Silicon
Thermistors

MKIDs

Microwave Kinetic Inductance Detectors (MKIDs)



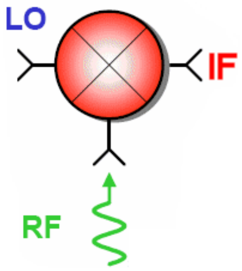
|E|
a
hν
Δ
C
$N_S(E)$
b
hν
0
-10
Power (dB)
c
δP
δf
f_0
f
Phase
d
δθ
f_0
f

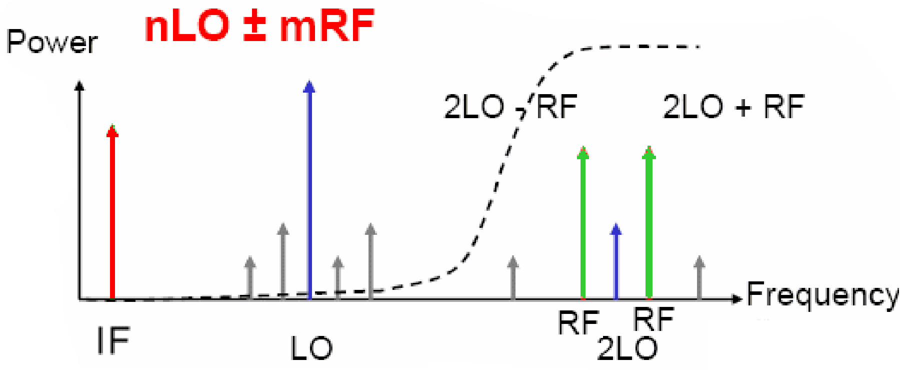


Pulses from 6 keV photons
(Day et al., Nature 425, 2004)

Coherent Sensors: Mixers

Mixers can be fundamental, subharmonic. and balanced.





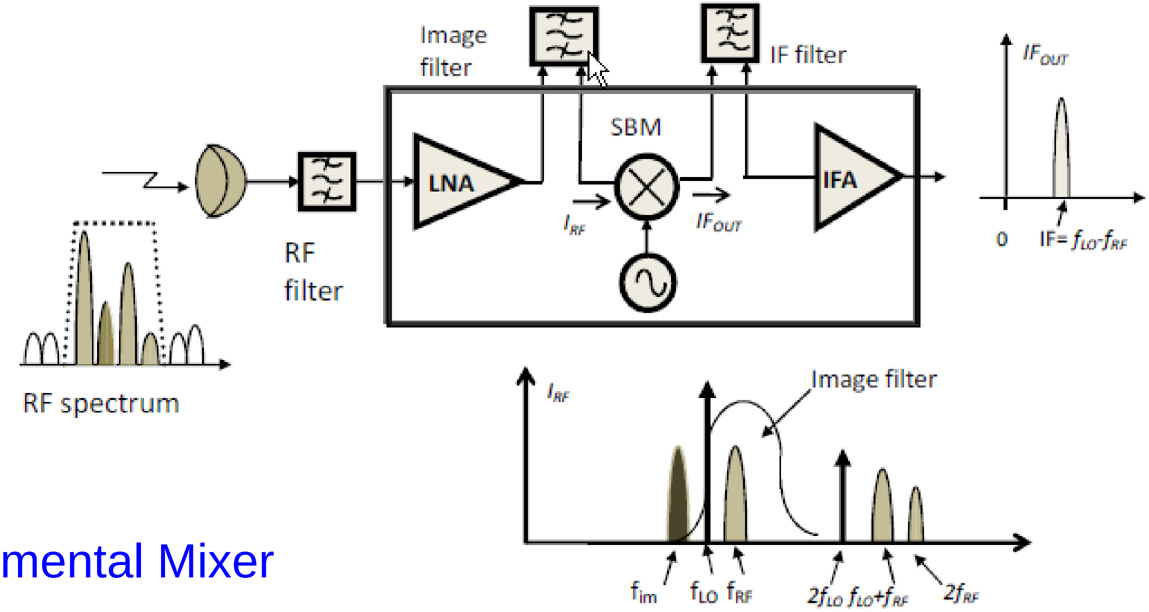
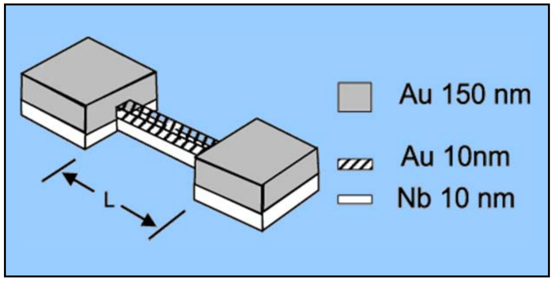


Image filter
IF filter
SBM
LNA
IFA
I_{RF}
IF_{OUT}
RF filter
RF spectrum
IF_{OUT}
0
IF= f_{LO}-f_{RF}
I_{RF}
Image filter
f_{im}
f_{LO}
f_{RF}
$2f_{LO}$
f_{LO}+f_{RF}
$2f_{RF}$

Fundamental Mixer

Hot Electron Bolometer Mixers

Hot Electron Bolometer (HEB) Mixers:


L
Au 150 nm
Au 10nm
Nb 10 nm

Diffusion cooled or Phonon cooled.

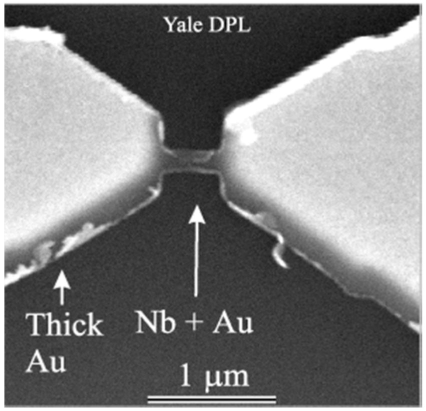
Operating frequency: 500 GHz to 10 THz.

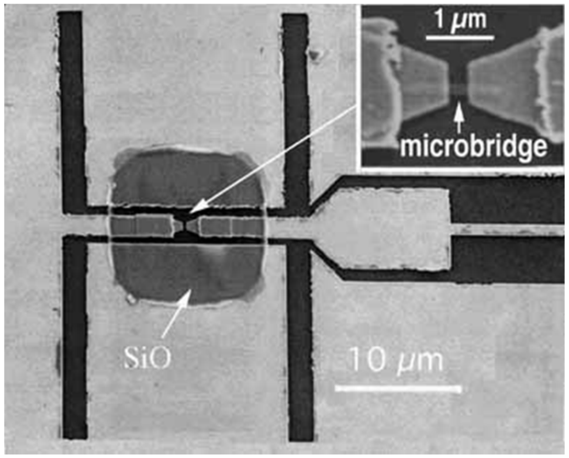
Operating temperature: 4K or below.

Local Oscillator Power: 100 nW range (≈ 1-2 µW with optical losses).

Receiver noise temperature @ 500 GHz: ≈ 600K.

Mixer conversion loss @ 500 GHz: ≈ 10 - 15 dB.


Yale DPL
Thick Au
Nb + Au
1 µm

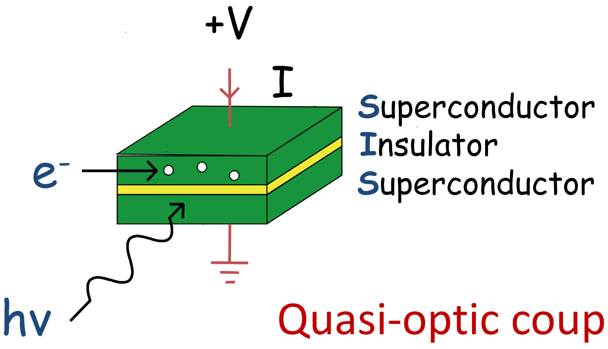

1 µm
microbridge
SiO
10 µm

- Planar technology
- Waveguide or quasi-optical

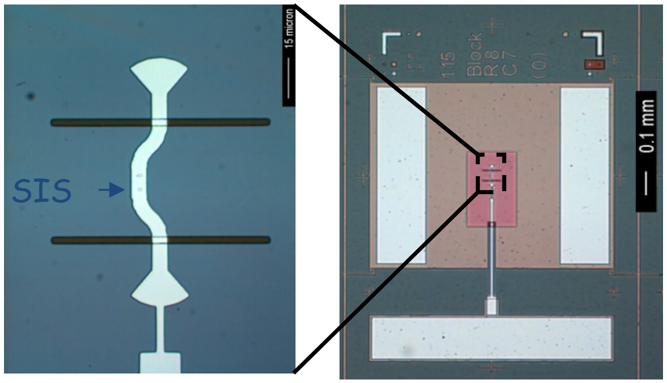
IF bandwidth is an issue!

SIS Mixers

Superconductor Insulator Superconductor (SIS) Mixers:


+V
I
e⁻
hν
Superconductor
Insulator
Superconductor

Quasi-optic coupling with twin-slot antennas


SIS
15 micron
0.1 mm

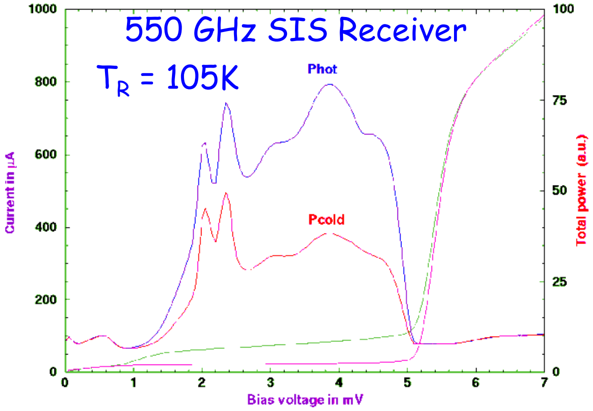
Operating frequency: 100 GHz to 1.2 THz (NbTiN).

Operating temperature: 4K or below.

Local Oscillator Power: 50 - 100 µW range.

Receiver noise temperature @ 500 GHz ≈ 85K.

Mixer conversion loss @ 500 GHz ≈ 1 dB.



- Planar technology
- Waveguide or quasi-optical
- Array integration: possible, not that easy
- IF bandwidth: Not an issue

Schottky Diode Mixers

Schottky Diode Mixers:

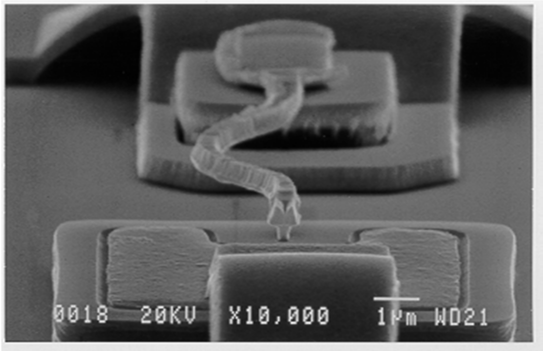
Operating frequency: Up to 5 THz and beyond.

Operating temperature: Room Temp. to 20K.

Local Oscillator Power: 0.3 – 1 mW range.

Receiver noise temperature @ 500 GHz ≈ 1800K.

Mixer conversion loss @ 500 GHz ≈ 8 dB.

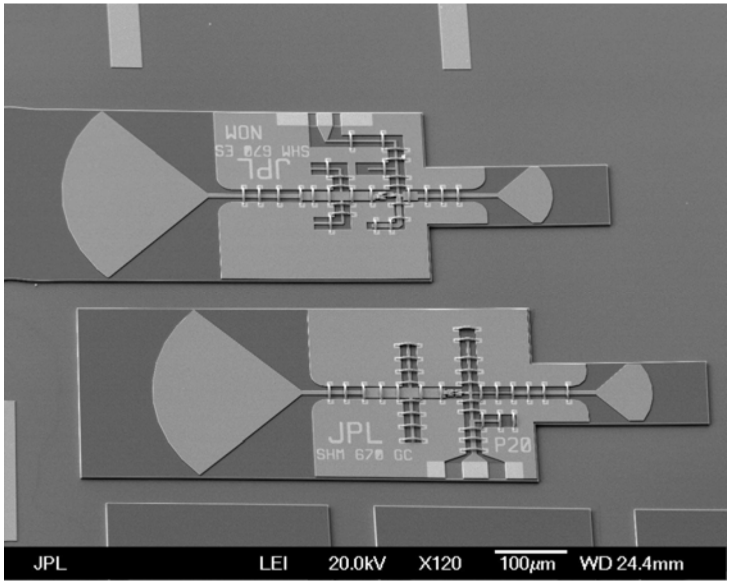


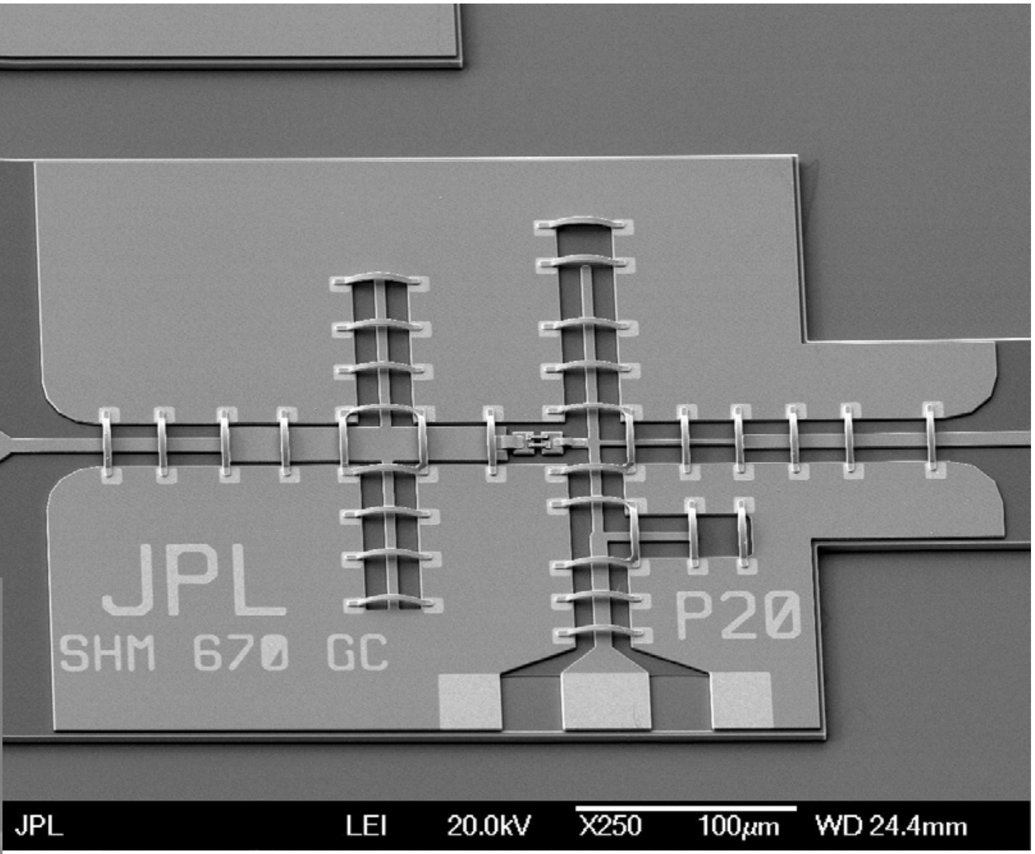
2.5 THz Schottky diode mixer
(anode size: 1 µm X 0.2 µm.)

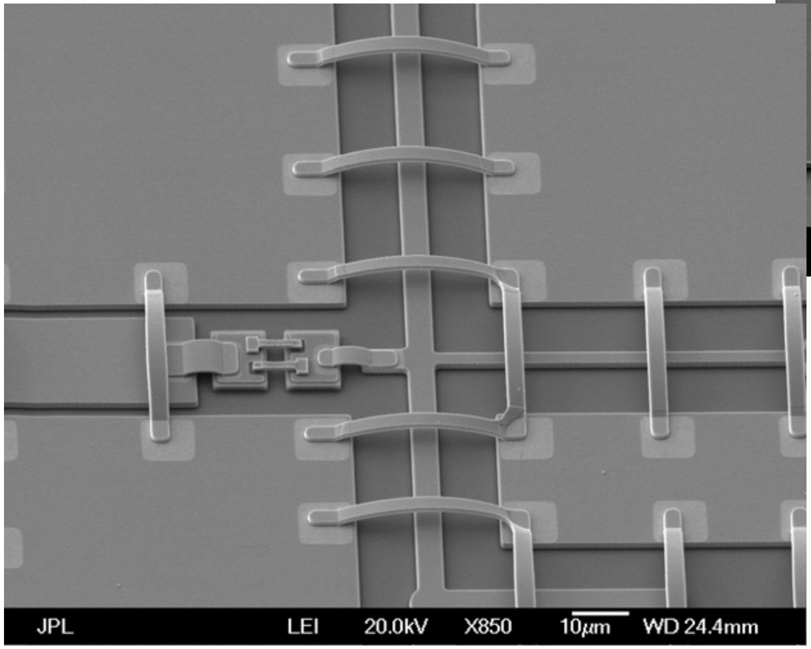
- Planar diode technology
- IF bandwidth: Not and issue
- Robust and mature technology
- LO pump power is an issue

Major advantage: can operate at room temp. and lower

Mixer Design

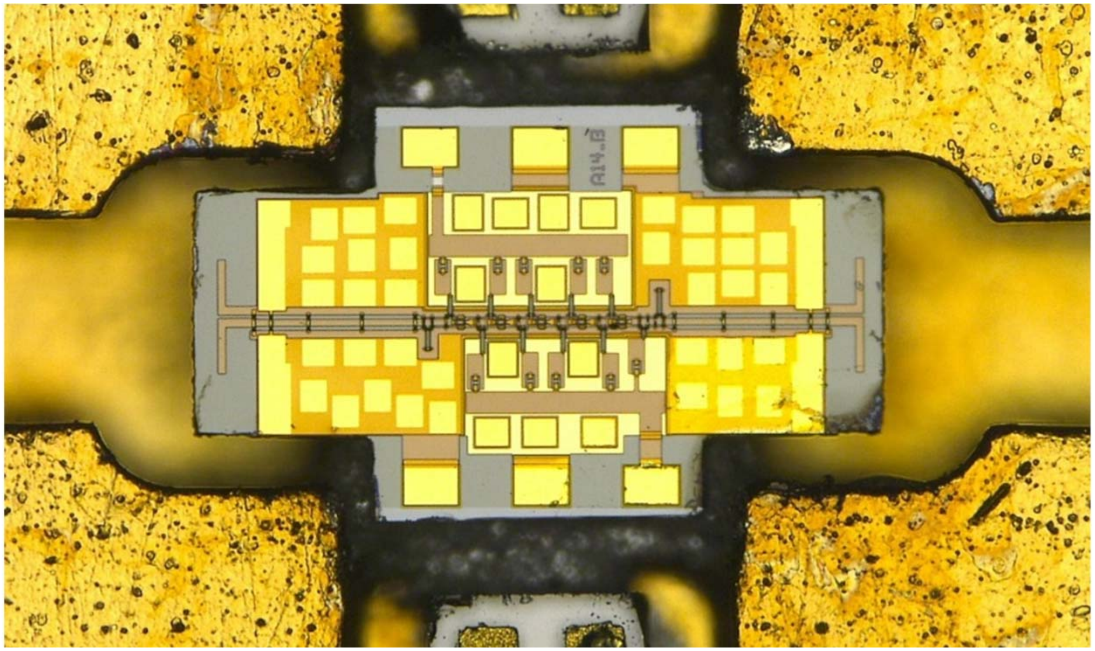

NOM
SHM 670 E3
JPL
JPL
SHM 670 GC
P20
JPL
LEI
20.0kV
X120
100µm
WD 24.4mm


JPL
SHM 670 GC
P20
JPL
LEI
20.0kV
X250
100µm
WD 24.4mm

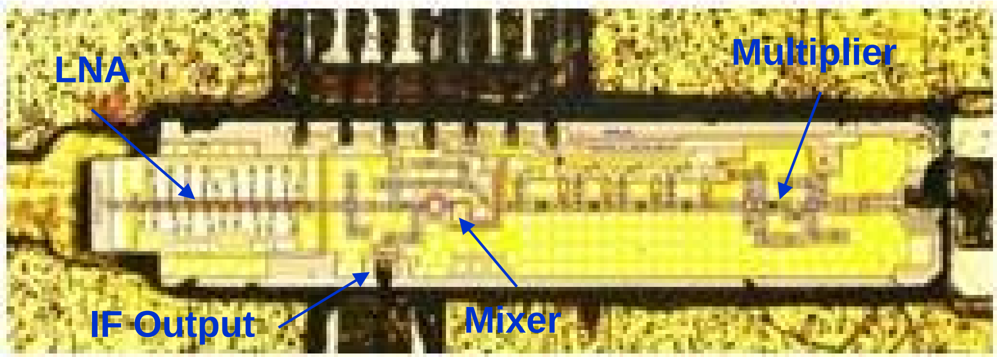

JPL
LEI
20.0kV
X850
10µm
WD 24.4mm

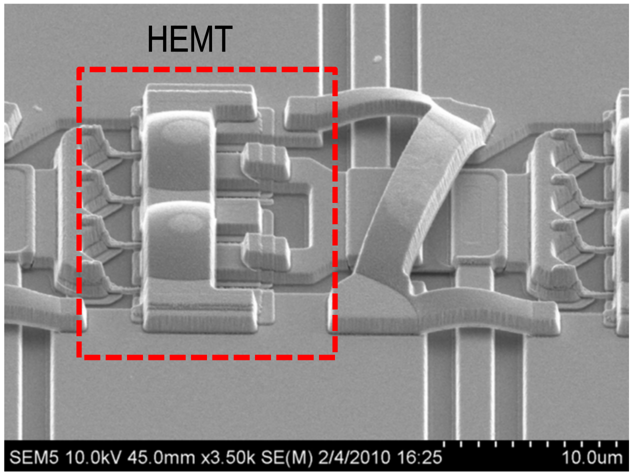
670 GHz CPW Schottky Diode Subharmonic Mixer.

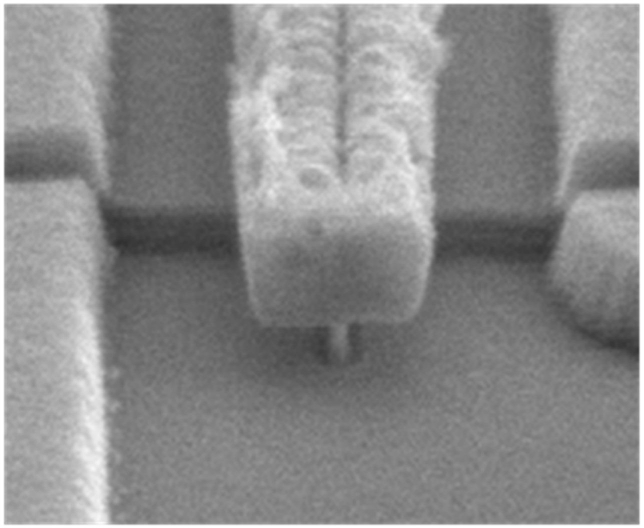
Terahertz Transistors at 650 GHz



High Electron Mobility Transistor (HEMT) based Amplifier

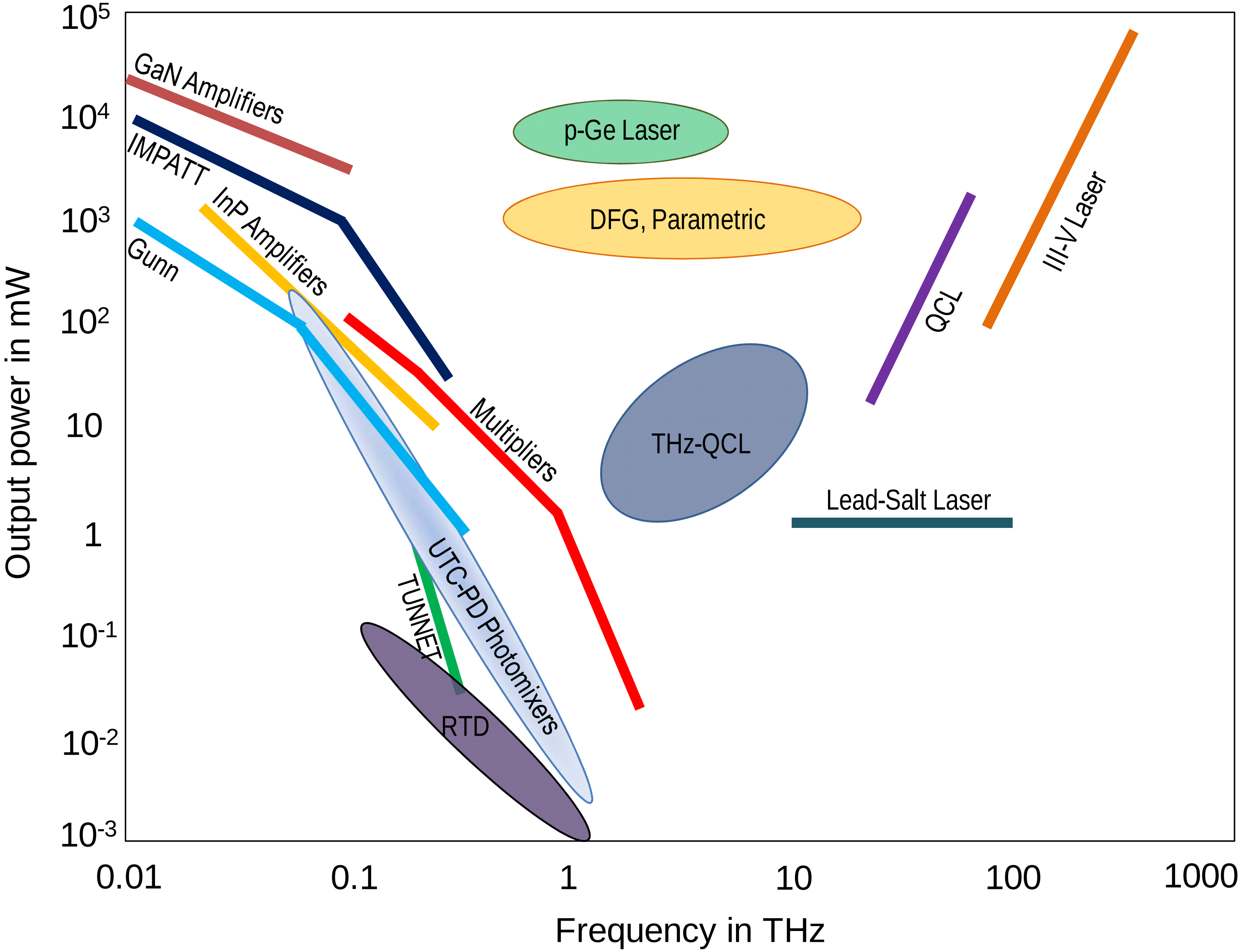

LNA
Multiplier
IF Output
Mixer


HEMT
SEM5 10.0kV 45.0mm x3.50k SE(M) 2/4/2010 16:25
10.0um



Ref: W. Deal, et al., IEEE Trans. THz Sc. Tech., vol. 1, no. 1, pp. 25-32, Sept. 2011

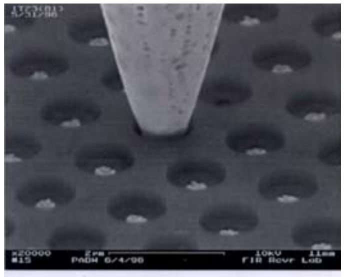
Terahertz Sources



Ref: G. Chattopadhyay, IEEE Trans. THz Sc. Tech., vol. 1, no. 1, pp. 33-53, Sept. 2011

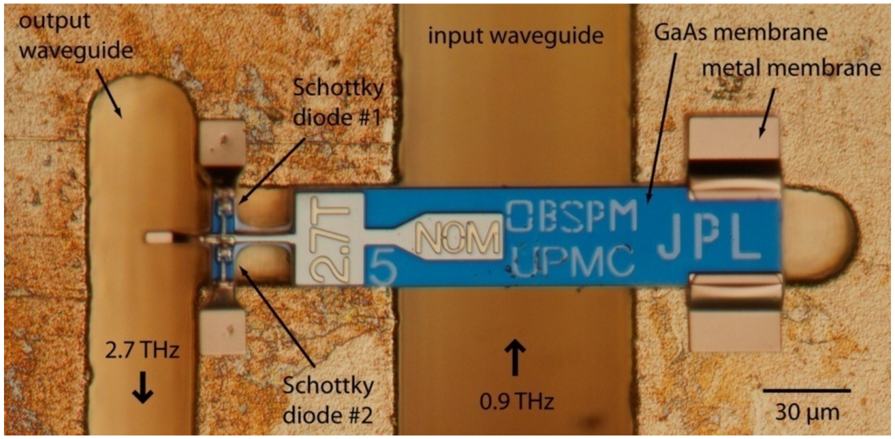
Terahertz Sources

Multiplied Source: Progress due to MMIC power amps, device modeling, block machining, and planar diodes.



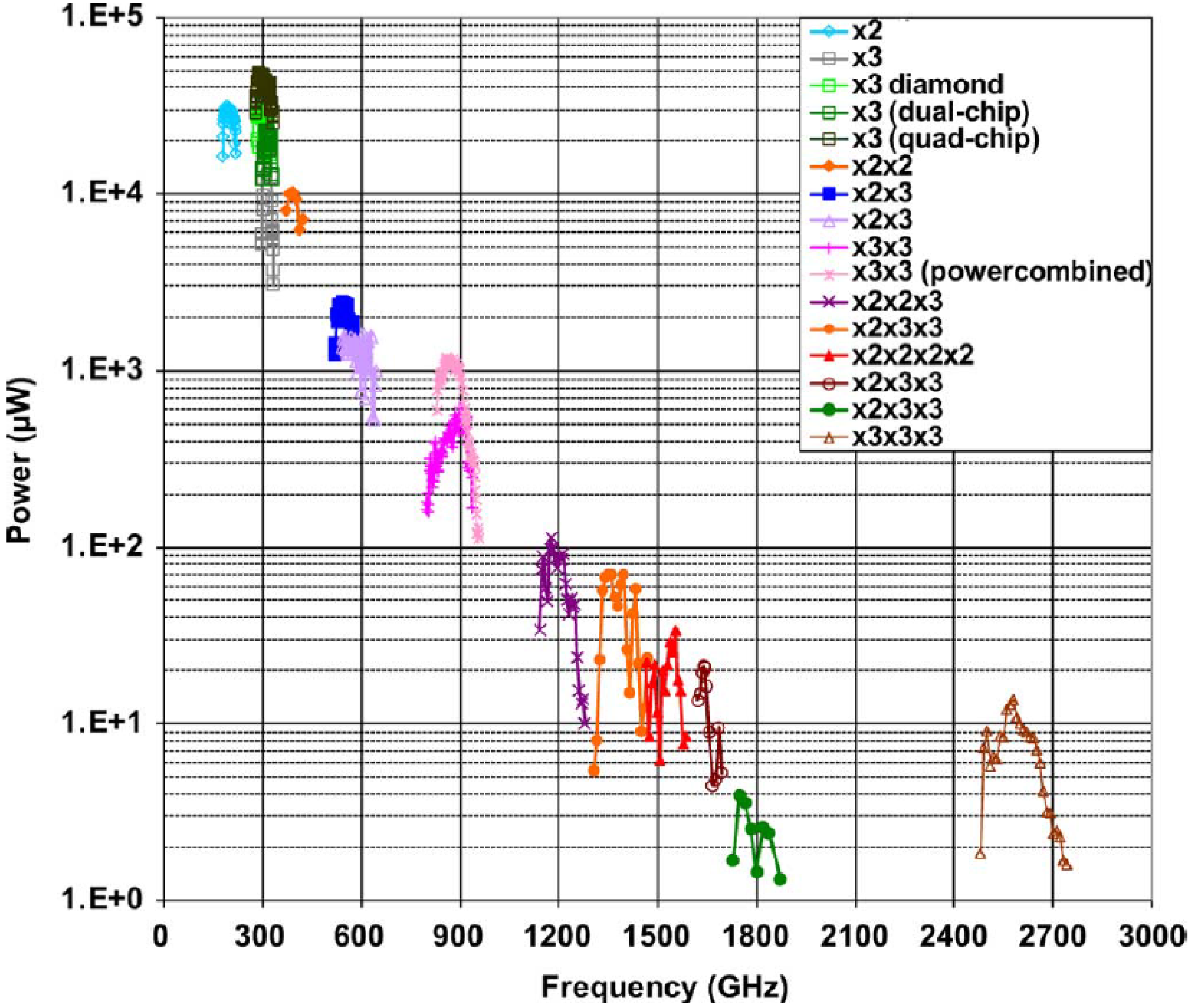
Whiskered Diode

Typical performance of broadband solid-state frequency multiplied sources:


output waveguide
Schottky diode #1
input waveguide
GaAs membrane
metal membrane
2.7T
5
NOM
OBSPM UPMC
JPL
2.7 THz ↓
Schottky diode #2
↑ 0.9 THz
30 µm

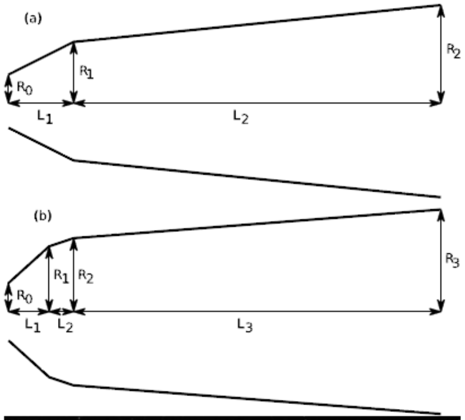
35% efficiency at 200 GHz,
20% efficiency at 400 GHz,
10% efficiency at 800 GHz,
3% efficiency at 1600 GHz,
1% efficiency at 2700 GHz
with more than 14% BW.

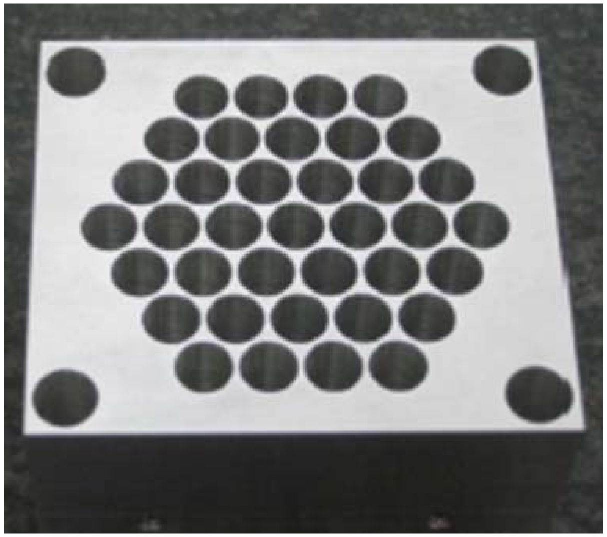
Status of Terahertz Sources

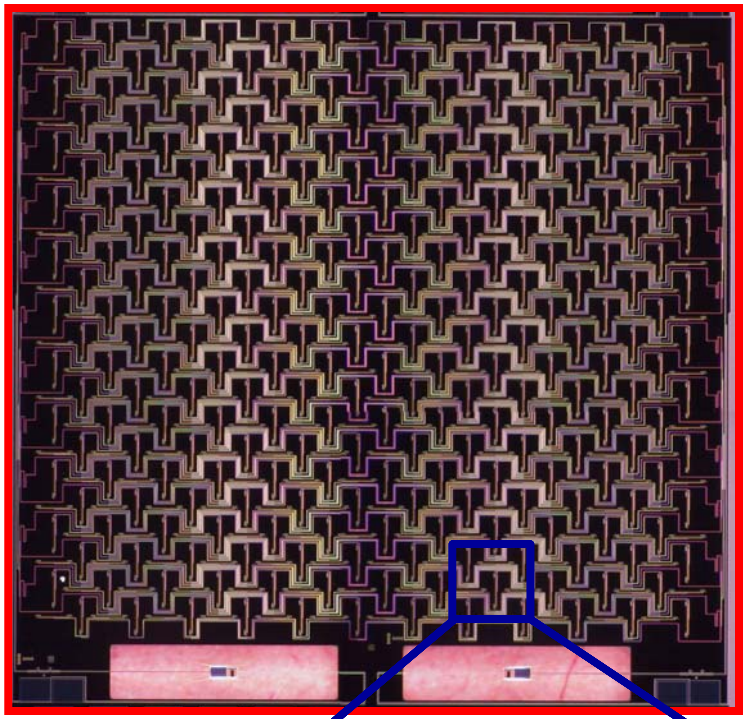


Ref: G. Chattopadhyay, IEEE Trans. THz Sc. Tech., vol. 1, no. 1, pp. 33-53, Sept. 2011

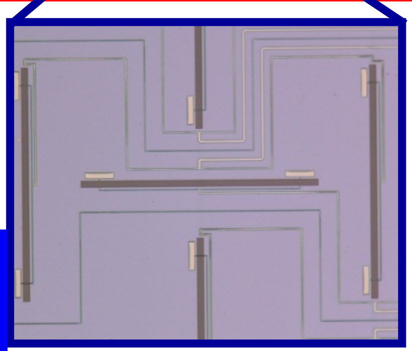
Terahertz Antennas

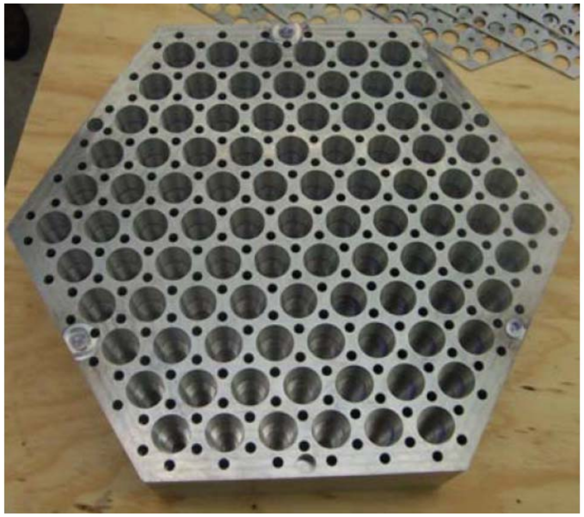

(a)
R2
R1
R0
L1
L2
(b)
R3
R1
R2
R0
L1
L2
L3

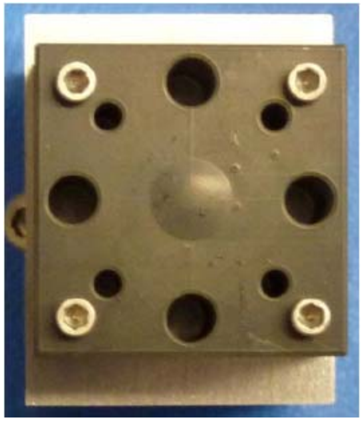


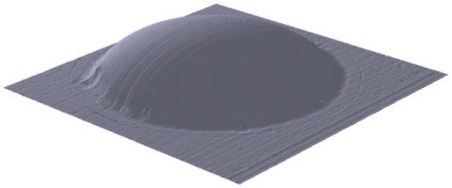


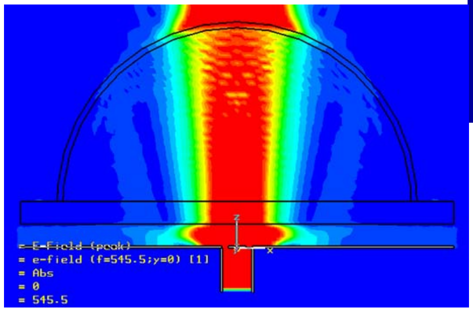
Ref: J. Leech et al., “Experimental investigation of a low-cost, high performance focal –plane horn array,” IEEE Trans. Terahertz Sc. Tech., vol. 1, no. 2, Jan. 2012.











Terahertz Systems: Imaging Radar

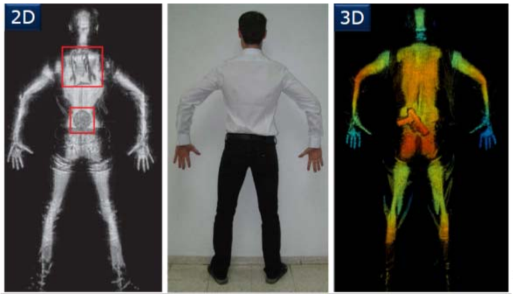
Top performers in concealed object detection:

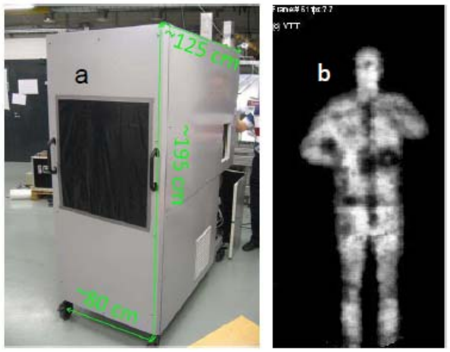
Close-range/portal:

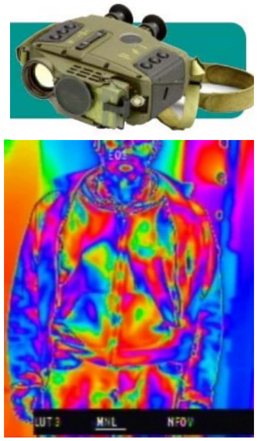
- X-ray scanning (Rapiscan, AS&E)
- Active mm-wave portals (L3-Provision, Rhode-Schwartz)

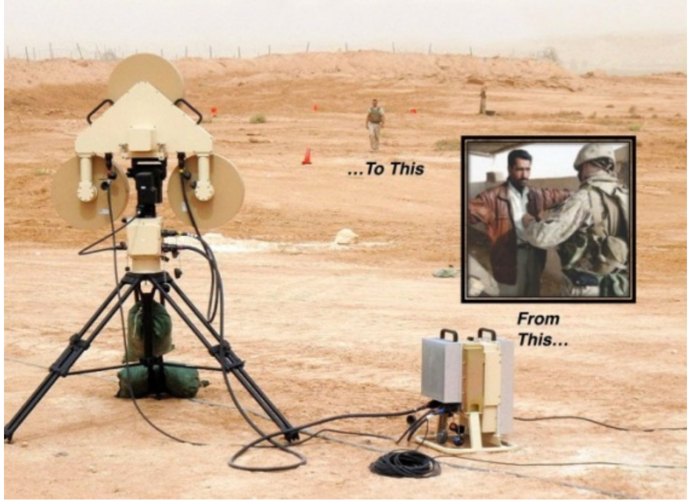
Standoff-range:

- Active microwave (Counterbomber)
- Passive thermal IR (Elbit)
- Passive mm-wave (Millivision, Thruvision)
- Passive Terahertz (VTT-Finland, IPhT-Germany)
- Active Terahertz (**JPL**, St. Andrews, PNNL)



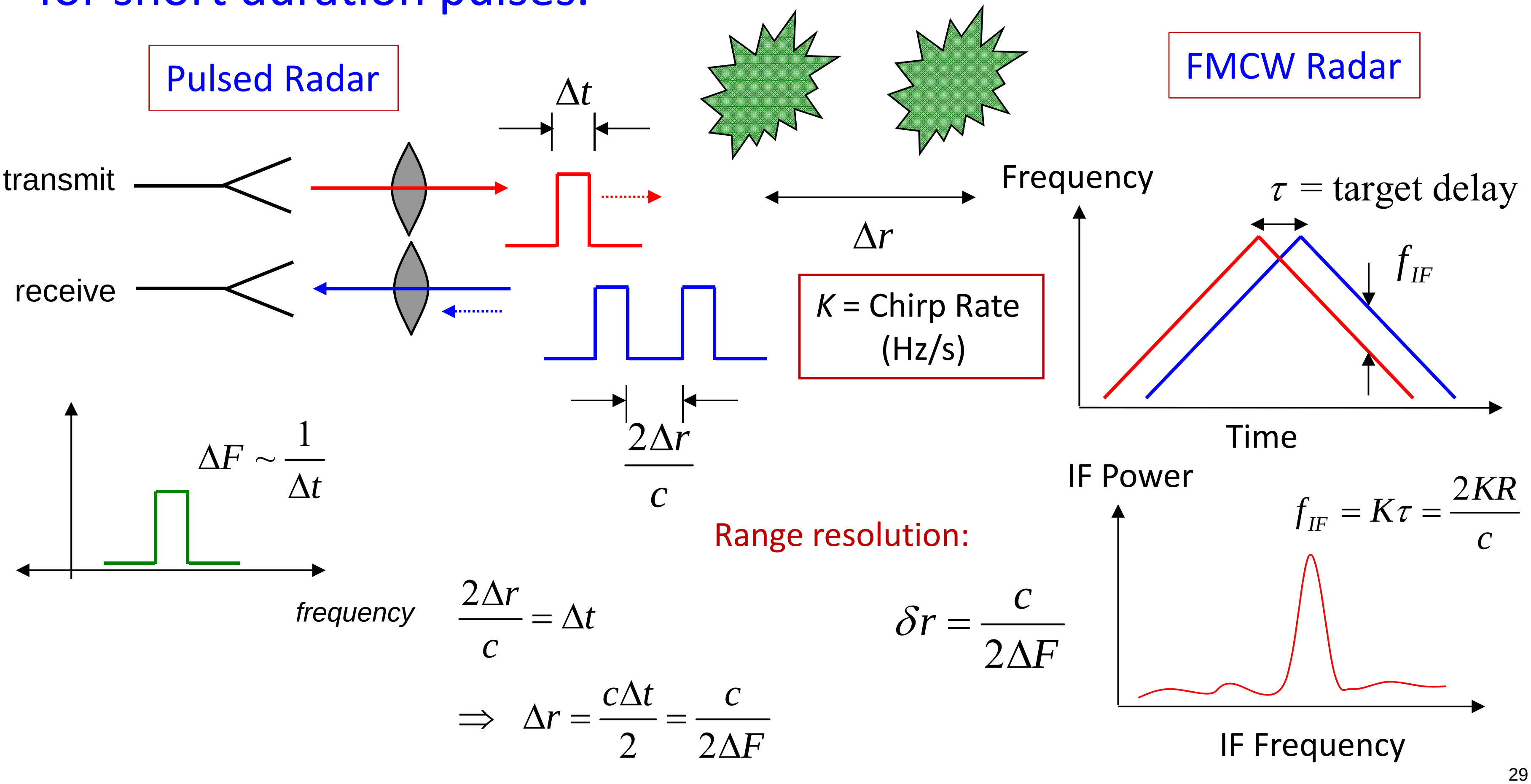

a
~125 cm
~195 cm
~80 cm
b
VTT




...To This
From
This...

Terahertz FMCW Radar Detection

Frequency modulated continuous wave (FMCW) radar is preferred over common pulse radar when the maximum available transmit power is low to obtain a high signal to noise ratio (SNR) for short duration pulses.


Pulsed Radar
FMCW Radar
Δt
transmit
receive
Δr
Frequency
τ = target delay
f_{IF}
K = Chirp Rate (Hz/s)
$\frac{2\Delta r}{c}$
Time
$\Delta F \sim \frac{1}{\Delta t}$
frequency
IF Power
$f_{IF} = K\tau = \frac{2KR}{c}$
IF Frequency

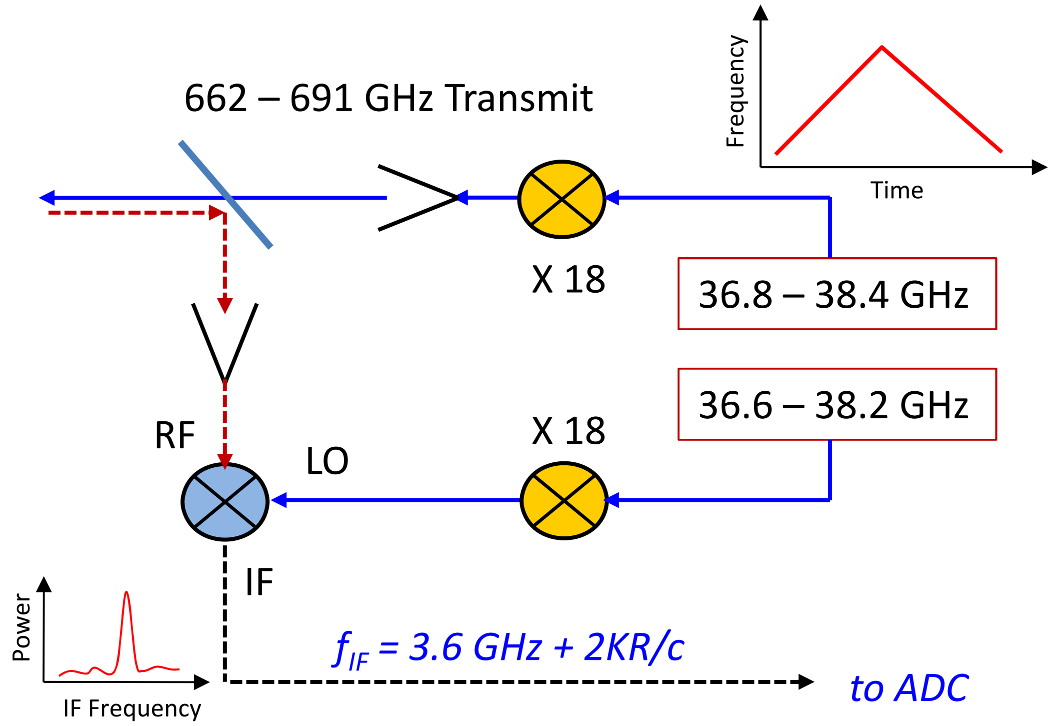
$$\frac{2\Delta r}{c} = \Delta t$$

$$\Rightarrow \quad \Delta r = \frac{c\Delta t}{2} = \frac{c}{2\Delta F}$$

Range resolution:

$$\delta r = \frac{c}{2\Delta F}$$

THz FMCW Radar Detection


662 – 691 GHz Transmit
Frequency
Time
X 18
36.8 – 38.4 GHz
36.6 – 38.2 GHz
X 18
RF
LO
IF
Power
IF Frequency
f_{IF} = 3.6 GHz + 2KR/c
to ADC

Transmitted wave amplitude:

$$S_T(t) = \exp[j\Phi_T(t)]$$

Time-dependence of the chirped frequency is contained in the transmit phase function:

$$\Phi_T(t)/2\pi = f_0 t + \frac{1}{2}K\ t^2$$

f_0 is the chirp's starting frequency.

After reflection from a target at range R, the received signal's phase function:

$\Phi_R(t) = \Phi_T(t - 2R/c)$ because of the round-trip time delay (c=speed of light)

In the receiver mixer, this signal is multiplied with the LO signal which has a phase function similar to the transmitted signal but with an offset starting frequency, $f_0 + f_\Delta$:

$$\Phi_{\mathrm{LO}}(t)/2\pi = (f_0 + f_\Delta)t + \frac{1}{2}K\ t^2$$

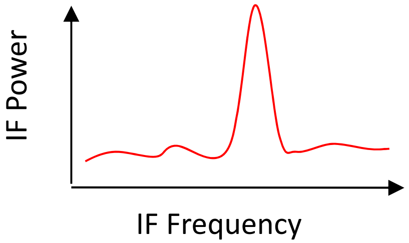
f_Δ in this case is 3.6 GHz

Range Accuracy and Resolution

There is an important distinction in FMCW radar of a single measurement between *accuracy* and *resolution*.

Accuracy: How well the range to a single target can be determined.

What does that mean in terms of FMCW radar measurements?



The IF spectrum with dominant peak (or tone) from a single target, the range accuracy corresponds to the uncertainty of the peak's centroid location.

How does that depend on the system performance?

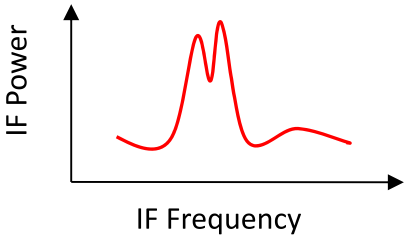
It depends on the SNR of the detected signal and the amount of signal averaging done, and is basically independent of the peak width.

For a bright point targets with large SNR, the range accuracy is limited by the residual motion or vibration of the radar itself (for our THz radar: ~ 0.5mm).

For THz radar imaging applications, absolute range ***accuracy*** is not nearly as important as the ***range resolution***.

Range Resolution

Range Resolution: The minimum distance that two targets can be separated along the radar's line of sight before they are indistinguishable.



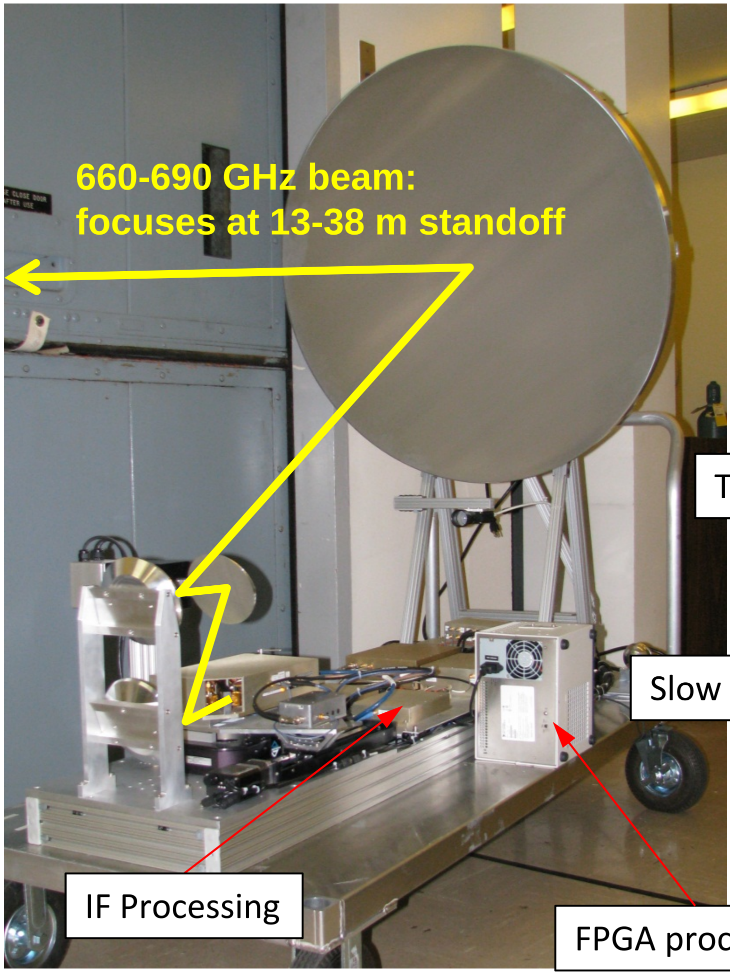
The ***range resolution*** of an ideal FMCW radar depends only on the radar's ***bandwidth*** and is independent of ***SNR***.

Consider the situation of two closely spaced targets generating an IF signal composed of two nearby frequency tones.

It is how well these tones can be ***spectrally resolved***, i.e., the ***width*** of each ***tone***, that determines radar's range resolution.

$$\delta r_{\min} = \frac{c \cdot \delta f_{\min}}{2K} = \frac{c}{2K\Delta t_{\text{chirp}}} = \frac{c}{2\Delta F}$$

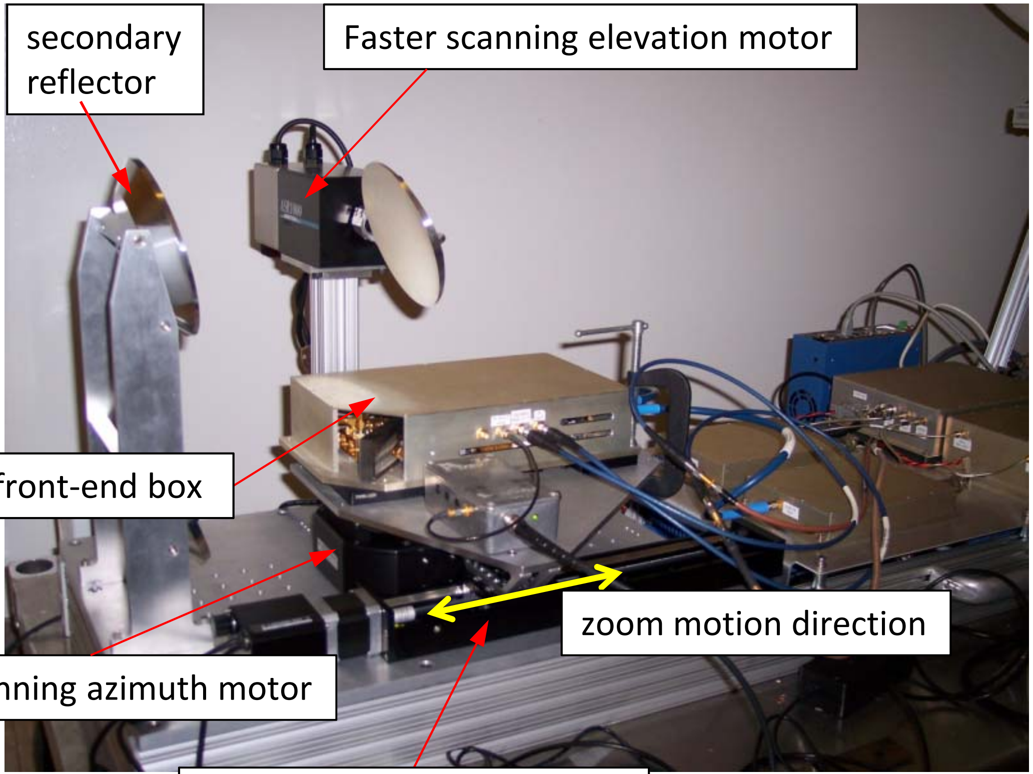
Terahertz FMCW Radar Imager



660-690 GHz beam:
focuses at 13-38 m standoff

IF Processing

FPGA processor



secondary reflector

Faster scanning elevation motor

THz front-end box

Slow scanning azimuth motor

zoom motion direction

Linear translation stage
for refocusing from 13-38 m

Ref: K. B. Cooper, G. Chattopadhyay, et al., IEEE Trans. THz Sc. Tech., vol. 1, no. 1, pp. 169-182, Sept. 2011

Terahertz FMCW Radar Imager

Operating Parameters:

Standoff range: 13 - 38 meters

Operating frequency: 660 - 690 GHz

Range resolution: < 1 cm

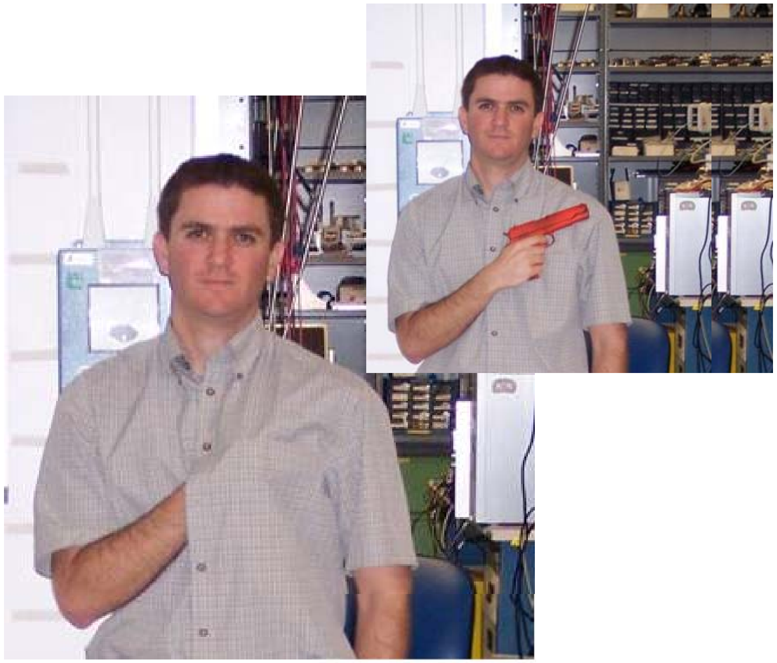
Cross-range resolution: 1 cm

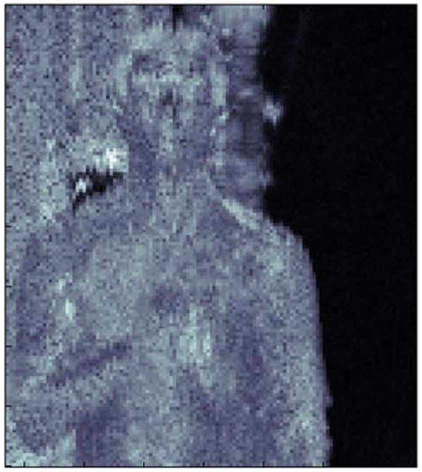
Output power: 0.5 mW

Min dwell time per pixel: 0.5 ms

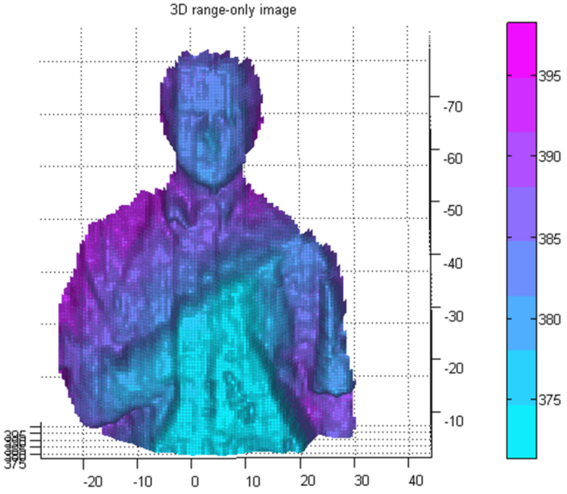
Max beam slew rate: 800 cm/s

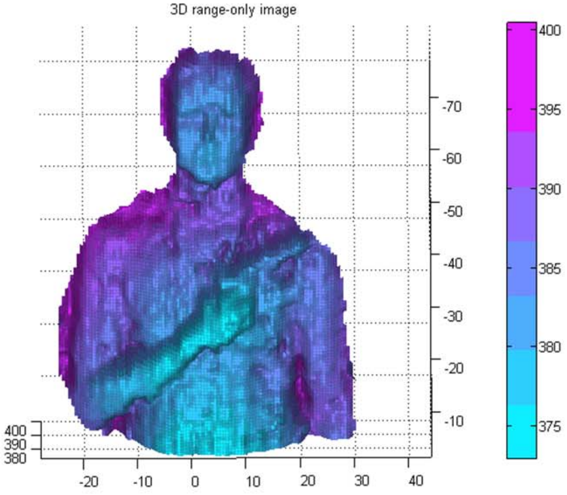
675 GHz Coherent Imaging Radar

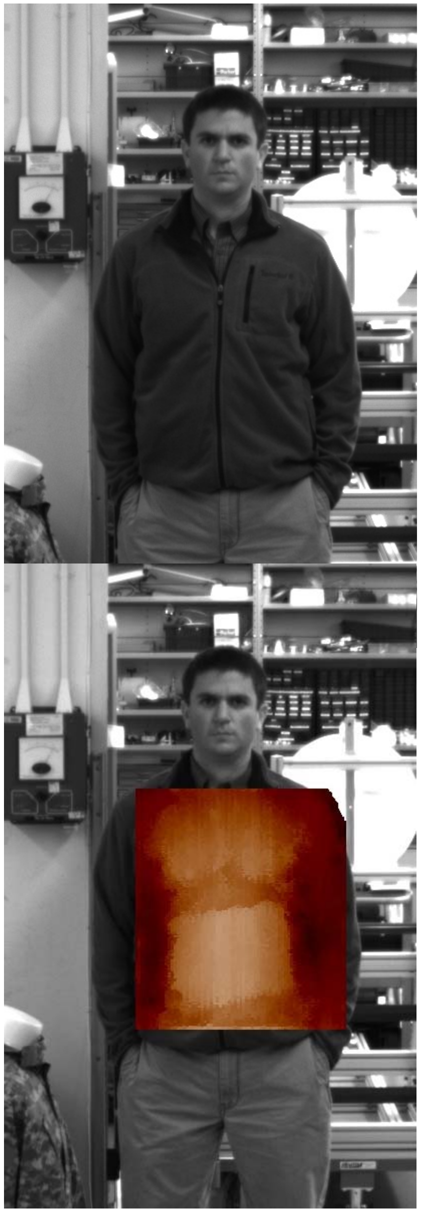




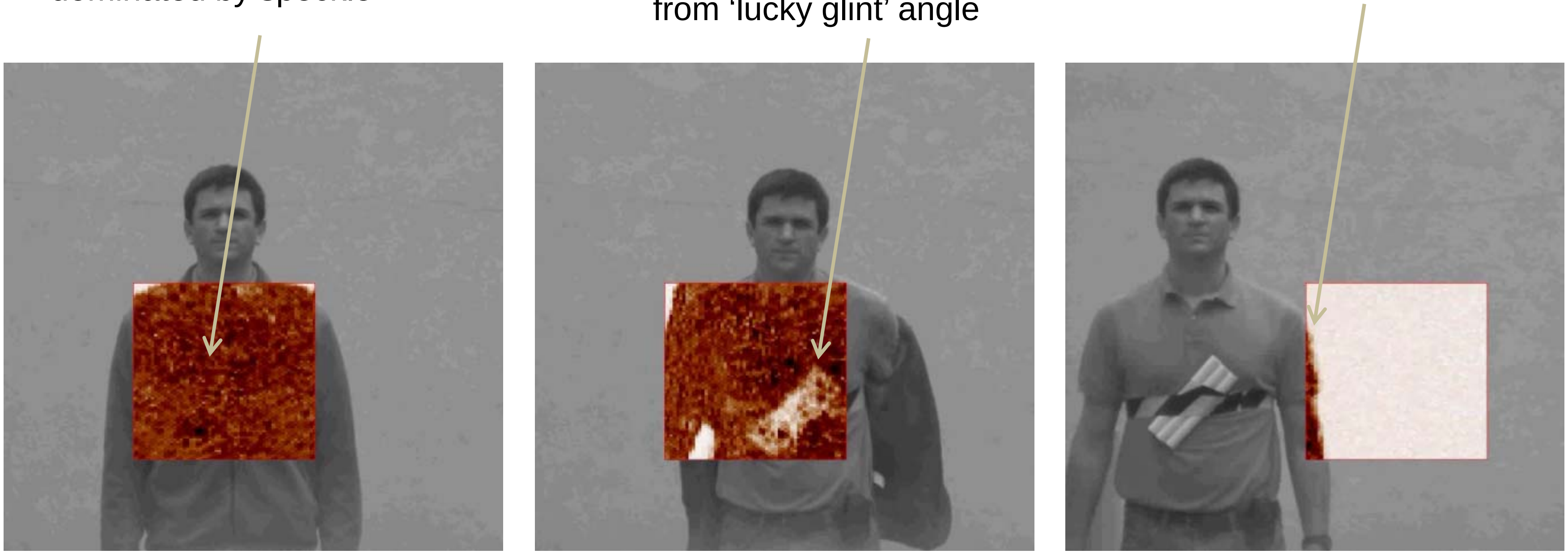
Intensity Only Image







Power-Only THz Imaging



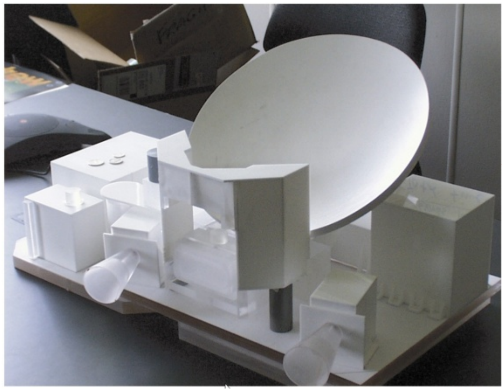
backscattering contrast dominated by speckle

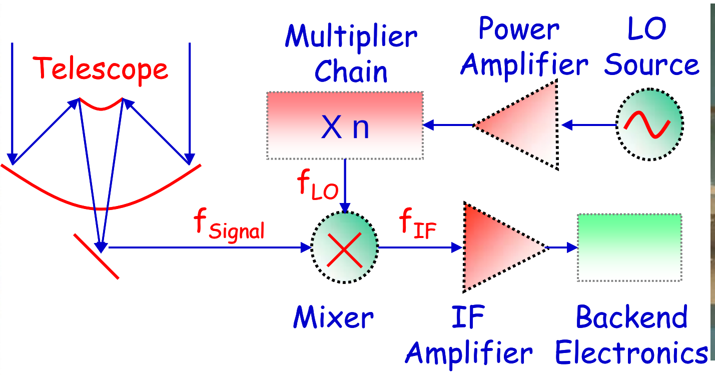
PVC pipes only detectable without a jacket, and only from ‘lucky glint’ angle

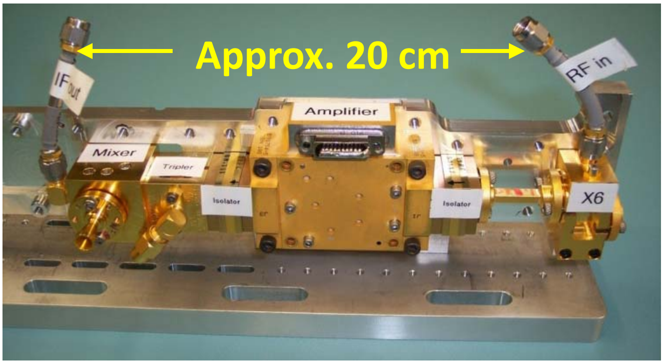
strong contrast: high SNR

Key Conclusion: Image contrast based on dielectric (i.e. material type) differences is TOTALLY SWAMPED by speckle effect from angle of beam-target incidence. Solution is 3-D radar imaging.

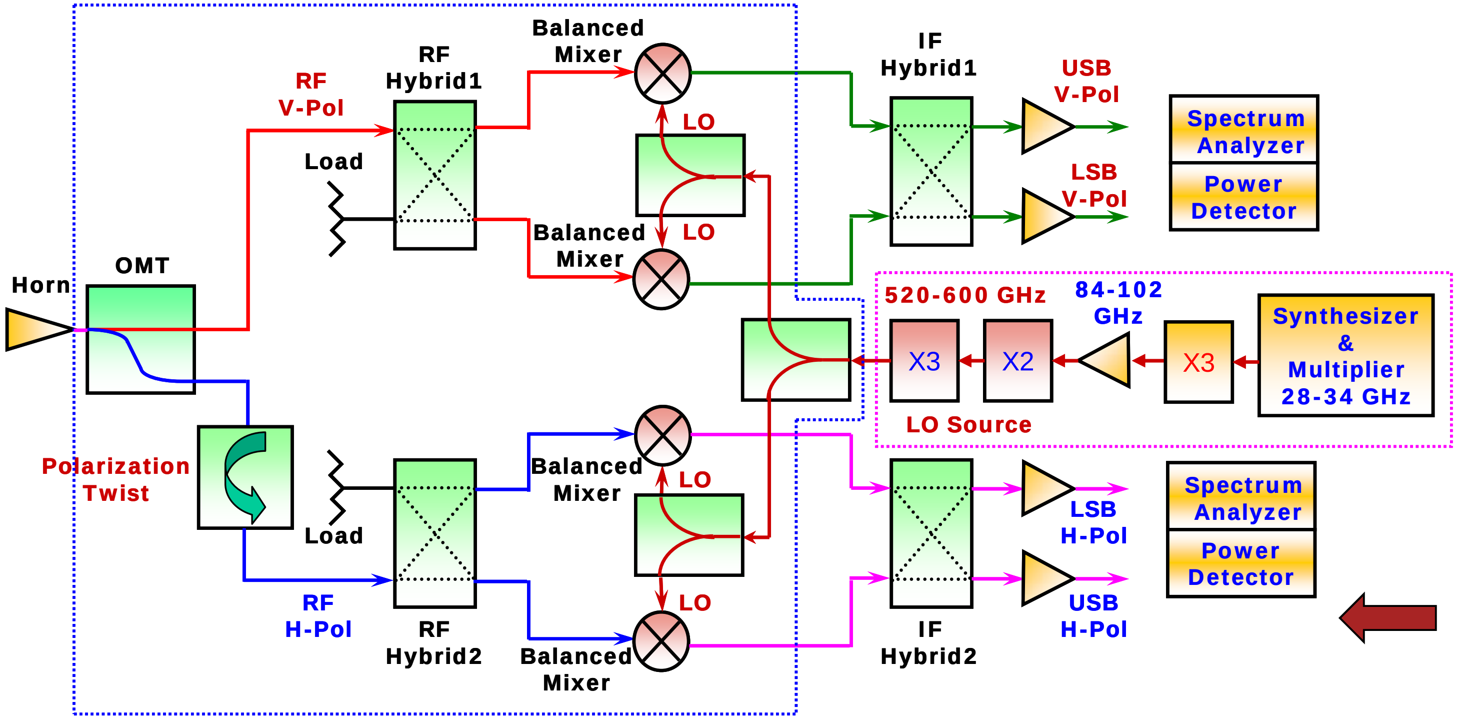
Next Generation Terahertz Receivers




Telescope
Multiplier Chain
X n
Power Amplifier
LO Source
f_{LO}
f_{Signal}
f_{IF}
Mixer
IF Amplifier
Backend Electronics

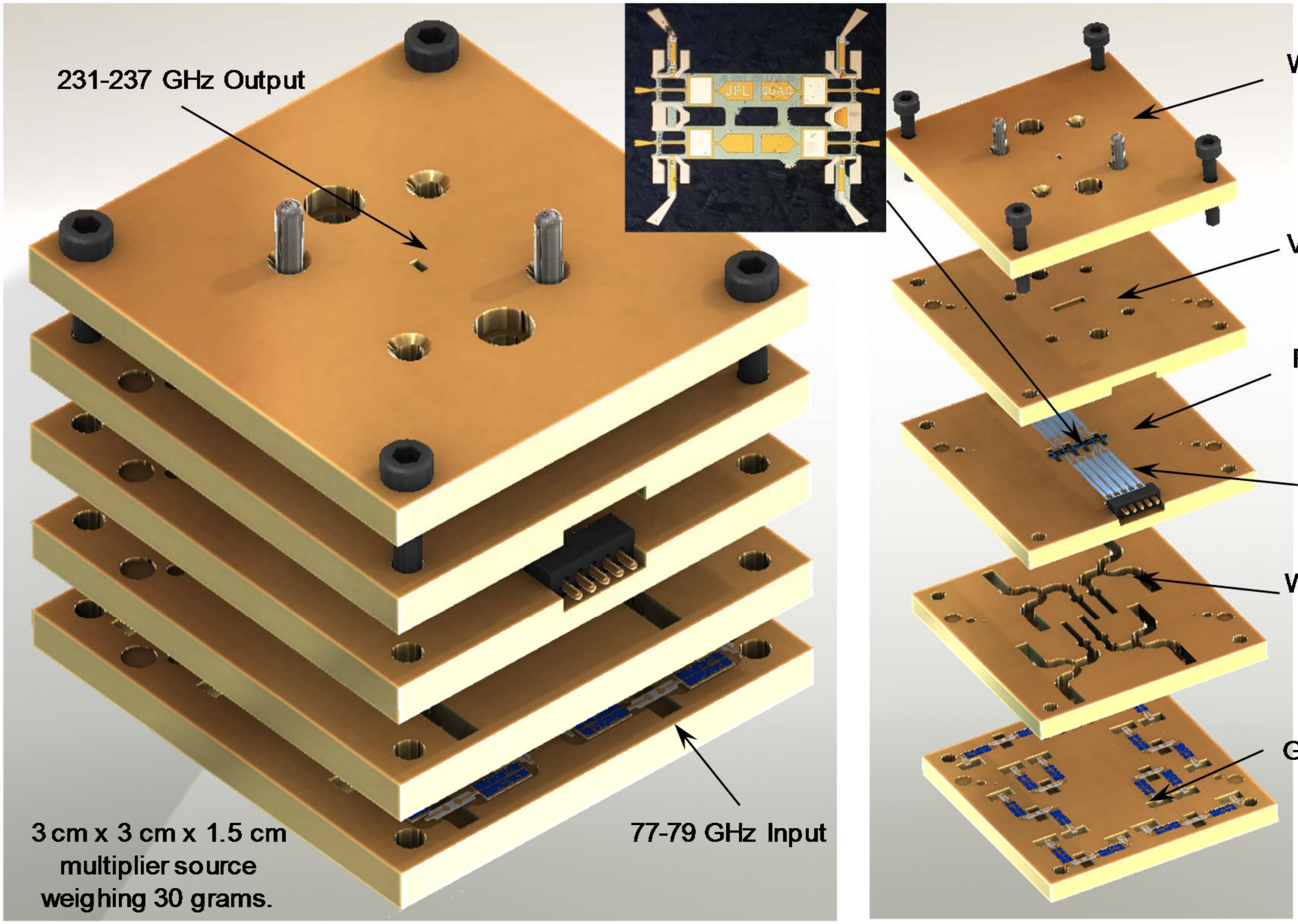

Approx. 20 cm
IF out
RF in
Amplifier
Mixer
Tripler
Isolator
Isolator
X6

Current generation heterodyne receiver system.


Horn
OMT
RF V-Pol
RF Hybrid1
Load
Balanced Mixer
LO
LO
Balanced Mixer
IF Hybrid1
USB V-Pol
LSB V-Pol
Spectrum Analyzer
Power Detector
520-600 GHz
84-102 GHz
X3
X2
X3
Synthesizer & Multiplier 28-34 GHz
LO Source
Polarization Twist
Load
Balanced Mixer
LO
LO
RF H-Pol
RF Hybrid2
Balanced Mixer
IF Hybrid2
LSB H-Pol
USB H-Pol
Spectrum Analyzer
Power Detector

Next generation receiver

Micromachined 1-Watt Source



231-237 GHz Output

77-79 GHz Input

3 cm x 3 cm x 1.5 cm
multiplier source
weighing 30 grams.

WR-4 UG-387/UM
Output Flange

Vertical Waveguide
Power Combiner

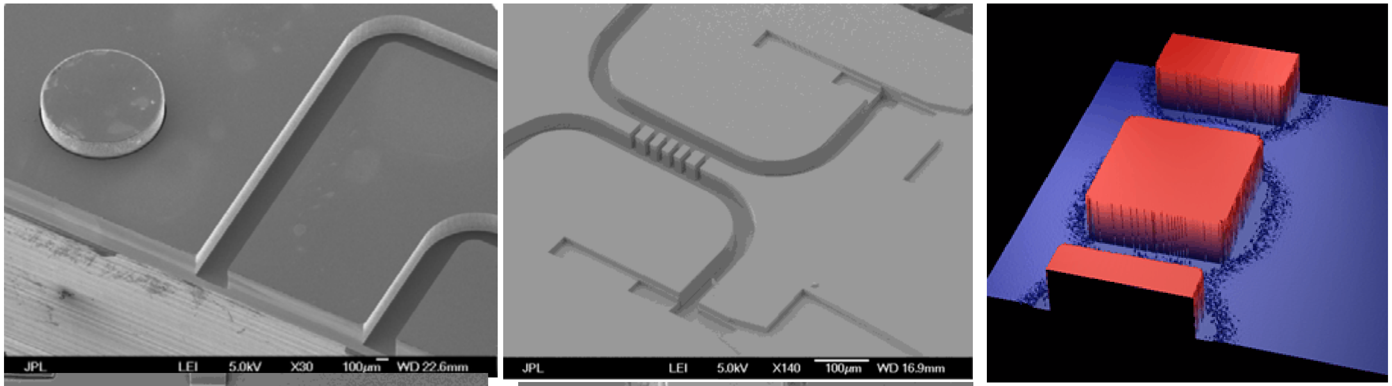
Frequency Multiplier
Chips

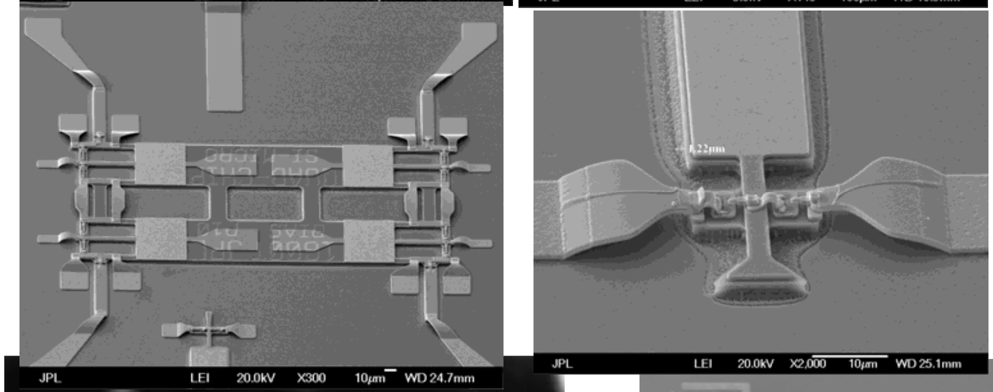
Multiplier Bias

Waveguide Matching
Circuits for Tripler

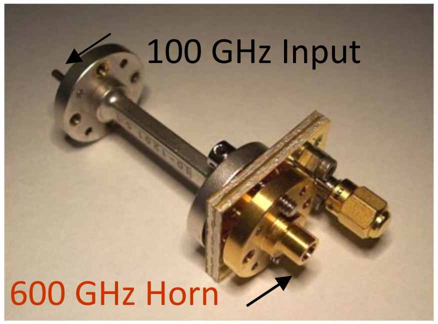
GaN Power Amplifiers

Micromachined Receiver on a Chip

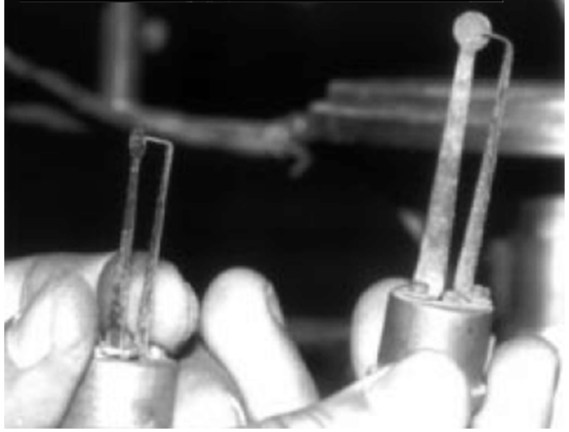

JPL LEI 5.0kV X30 100µm WD 22.6mm
JPL LEI 5.0kV X140 100µm WD 16.9mm


JPL LEI 20.0kV X300 10µm WD 24.7mm
JPL LEI 20.0kV X2,000 10µm WD 25.1mm

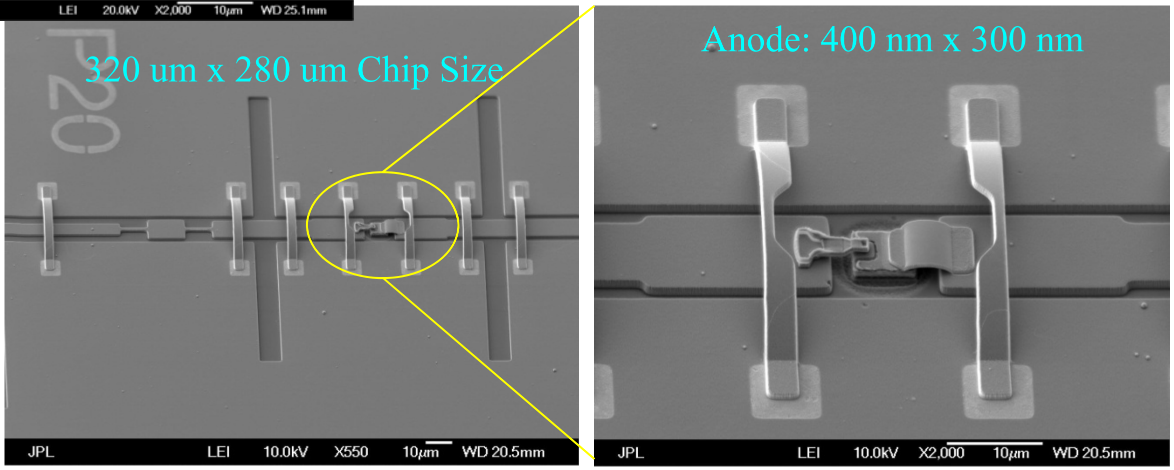
600 GHz Silicon
Micromachined
Components


100 GHz Input
600 GHz Horn

600 GHz Receiver
on a Chip
(20x25x3 mm
Si Package)



First diode (Coherer, J. C. Bose, 1896)

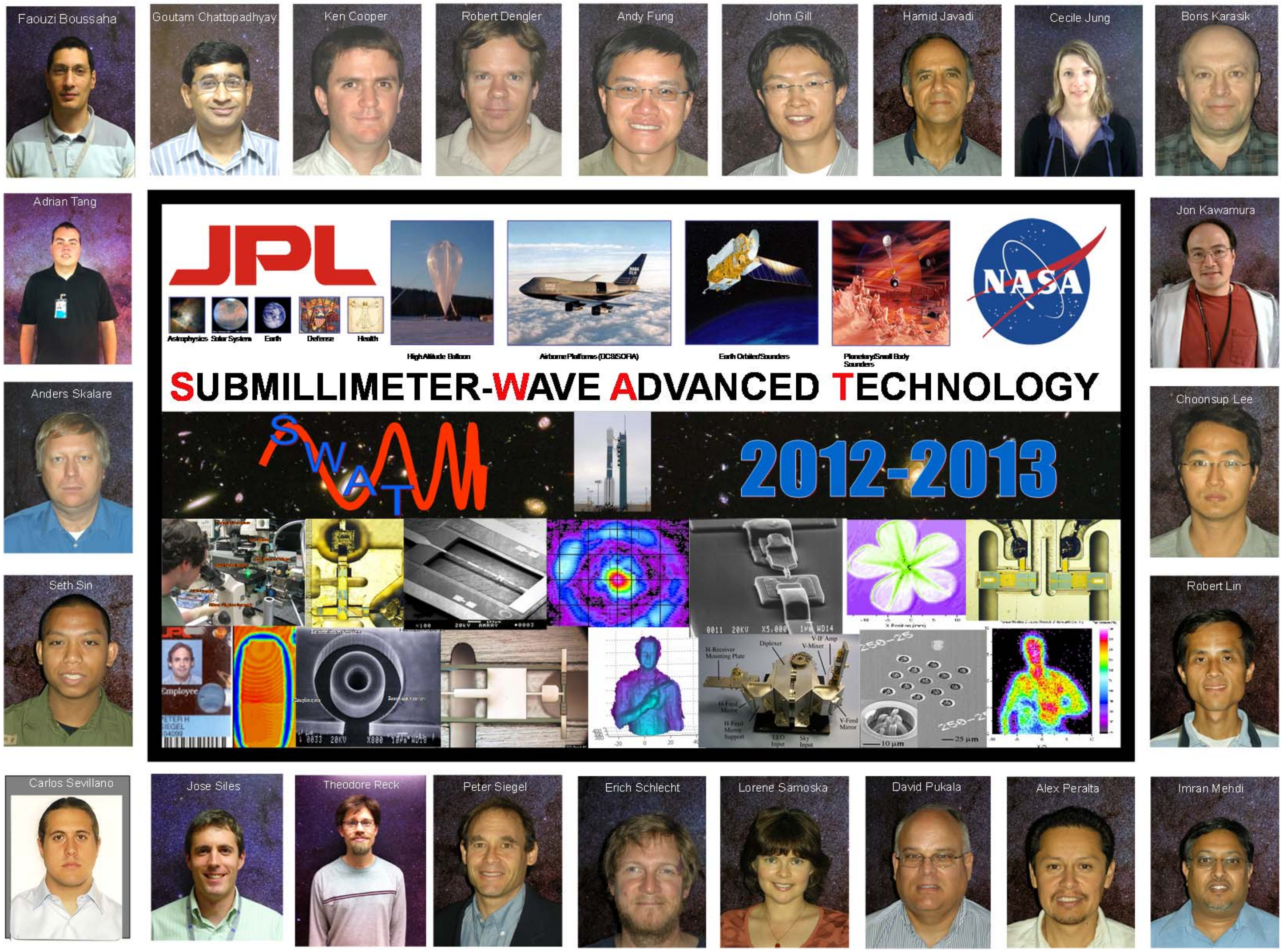

320 um x 280 um Chip Size
Anode: 400 nm x 300 nm
JPL LEI 10.0kV X550 10µm WD 20.5mm
JPL LEI 10.0kV X2,000 10µm WD 20.5mm

3.5 THz Integrated Mixer-Antenna Chip (JPL, 2010)

Summary

- Very exciting time for terahertz Scientists and Technologists.
- Traditional areas such as astrophysics, planetary, and Earth science applications are still driving the technology developments.
- New and emerging areas such as security and wireless power transfer is going to be the key drivers in future developments.

Acknowledgement


Faouzi Boussaha
Goutam Chattopadhyay
Ken Cooper
Robert Dengler
Andy Fung
John Gill
Hamid Javadi
Cecile Jung
Boris Karasik
Adrian Tang
Jon Kawamura
Anders Skalare
Choonsup Lee
Seth Sin
Robert Lin
JPL
Astrophysics
Solar System
Earth
Defense
Health
High Altitude Balloon
Airborne Platforms (DC8/SOFIA)
Earth Orbiter/Sounders
Planetary/Small Body Sounders
NASA
SUBMILLIMETER-WAVE ADVANCED TECHNOLOGY
SWAT
2012-2013
Carlos Sevillano
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Theodore Reck
Peter Siegel
Erich Schlecht
Lorene Samoska
David Pukala
Alex Peralta
Imran Mehdi

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